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TEXTURAL FEATURES OF THE ORDOVICIAN SANDSTONES OF ARKANSAS[1]

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ABSTRACT

The Ordovician sandstones of Arkansas which have been described are, in descending order, the St. Peter, Calico Rock, and Kings River. The last two are members of the Everton formation which is overlain unconformably by the St. Peter sandstone. The textural features of these sandstones are very similar, making it almost impossible to distinguish them in hand specimens, or microscopically. The textural features of the St. Peter as mapped in current publications describing the geology of northern Arkansas will be considered in detail.[2]

The St. Peter sandstone of Arkansas has been significantly altered since its deposition. This alteration has resulted from the deposition of silica upon the surfaces of the originally rounded and frosted grains, forming crusts and crystal faces bounding the original surfaces of the grains and crystals rising normal to the original surfaces. The effect of the secondary enlargement has been to decrease the porosity of the sandstone, to conceal the frosting, to produce pitting, to alter the sizes of the grains, to transform the grains into angular masses of quartz with interlocking boundaries, and to give the sandstone whatever degree of coherence it possesses. The source of the secondary silica was primarily in the zone of weathering, and secondarily from etching of the surfaces of the original grains and secondary quartz previously deposited on the original grains. Consequently, secondary enlargement is greatest near outcrops, in the originally more porous parts of the sandstone, and in the upper parts of the formation under thin cover. The extent of secondary enlargement determines the capacity of the sandstone as a reservoir for oil or water.

[1] Presented before Section E of the American Association for the Advancement of Science at Cleveland, January 1, 1931. Published with the permission of Mr. George C. Branner, director of the Arkansas Geological Survey.

Research Paper, No. 254, Journal Series, University of Arkansas.

[2] A. H. Purdue and H. D. Miser, Eureka Springs–Harrison Folio, No. 202, *Geologic Atlas of United States, U.S. Geol. Surv.* (1916).

H. D. Miser, "Deposits of Manganese Ore in the Batesville District, Arkansas," *U.S. Geol. Surv., Bull. 734* (1922).

Arkansas Geological Map, *Ark. Geol. Surv.* (1929).

Albert W. Giles, "St. Peter and Older Ordovician Sandstones of Northern Arkansas," *Ark. Geol. Surv., Bull. 4* (1930).

Since the completion two years ago of the manuscript of the report describing the Ordovician sandstones of Arkansas for the state geological survey, the textural features of the St. Peter sandstone have been studied further for the purpose of amplifying in greater detail the conclusions regarding texture embodied in the state report.[1] The St. Peter was chosen for the study because of its wide distribution in northern Arkansas and in the Mississippi Valley and also because it is the best known of the Ordovician sandstones represented in the Arkansas stratigraphic column, the others being limited to northern Arkansas as local developments in the widely extended Everton formation. The primary and secondary characters of the sandstones are so similar as to make the sandstones nearly identical megascopically and microscopically. The remarkable physical and chemical similarity of these sandstones is discussed at length in the state report.[2] The study has been appreciably facilitated by the opening of many fresh surfaces of the sandstone in the road-building program in progress in northern Arkansas during the last three years. The textural features to be described are porosity of the sandstone, size and shape of the grains, development of crystal faces, secondary enlargement, optical characters, and pitting, frosting, and etching of the grains. Since secondary enlargement is the most significant textural feature of the sand grains, the origin of the secondary silica and the major effects of secondary enlargement will also be considered.

POROSITY OF THE SANDSTONE

Twelve samples of St. Peter sandstone selected as representative of the formation in widely separated localities in northern Arkansas were submitted to A. F. Melcher for porosity determination.[3] Samples 1–10, inclusive, were collected from unweathered surfaces of the sandstone exposed in recent road-building operations, and hence their locations were relatively close to the surface; samples 11 and

[1] Albert W. Giles, "St. Peter and Older Ordovician Sandstones of Northern Arkansas," *Ark. Geol. Surv., Bull. 4* (1930).

[2] *Ibid.*, pp. 145–48, 155–57.

[3] Samples were collected from horizons mapped as St. Peter in the Eureka Springs–Harrison Folio, *U.S. Geol. Surv.* (1916); on the Arkansas Geological Map, *Ark. Geol. Surv.* (1929); and in *Bull. 4 of the Ark. Geol. Surv.* (1930.)

12 were collected underground 50 feet or more from the outcrop. The results of the determinations are given in Table I.

TABLE I

POROSITY OF THE ST. PETER SANDSTONE OF ARKANSAS

Sample	Percentage of Porosity by Volume	Description
No. 1	11.2	White sandstone
No. 2	8.9	White sandstone
No. 3	5.9	White sandstone
No. 4	10.0	White sandstone
No. 5	3.6	White, very hard sandstone
No. 6	8.8	White sandstone
No. 7	14.1	Grayish white sandstone
No. 8	10.8	White sandstone
No. 9*a*	11.2 (av. 9.9)	White sandstone, (*a*) sample from inside of chunk, (*b*) sample from outside of chunk more firmly cemented
No. 9*b*	8.6	
No. 10	6.0	Grayish white sandstone
No. 11	17.8	White sandstone
No. 12	15.3	White sandstone
Average	10.2	

The locations of the samples follow:

No. 1.—Northern Newton County, 5 miles north of Jasper, 25 feet below top of formation.

No. 2.—Southern Sharp County, near Cave City, near top of formation.

No. 3.—Southern Sharp County, south of Maxville, near bottom of formation.

No. 4.—Southern Carroll County, in Piney Creek near Metalton, near top of formation.

No. 5.—Northern Newton County, Marble City Falls, 25 feet below top of formation.

No. 6.—Northern Newton County, Marble City Falls, 40 feet below top of formation.

No. 7.—Southern Boone County, ½ mile east of Bellefonte, near middle of formation.

No. 8.—Western Izard County, on Pilot Knob, 27 feet below top of formation.

No. 9.—Northeastern Searcy County, at Big Creek Bridge, near bottom of formation.

No. 10.—Southeastern Sharp County, southwest of Calamine, near top of formation.

No. 11.—Southern Izard County, in Guion quarry at Guion, 50 feet back of main entrance to quarry, 30 feet below top of formation, and 50 feet or more below surface.

No. 12.—Southern Izard County, in Guion quarry at Guion, 75 feet back of main entrance to quarry, 30 feet below top of formation, and 60 feet or more below surface.

The porosity of the twelve samples averages 10.2 and ranges from 3.6 to 17.8, with six samples having a porosity of over 10 per cent. Sample No. 9 illustrates the appreciable variation in porosity which may occur within short distances. Samples 1–10, inclusive, collected near the outcrop have considerably lower porosities than the samples collected underground at Guion at a considerable distance from the outcrop.

Slichter has determined the minimum value of pore space in compact sand of rounded grains possessing the same diameters to be 25.95 per cent.[1] The element of volume in this arrangement is the rhombohedron, each sphere touching adjacent spheres at twelve points. The maximum value, 47.64 per cent, is obtained when the compacted grains of same diameter are so arranged as to touch each other at eight points, the element of volume in this arrangement forming the cube. It follows that under conditions of maximum compaction the pore space of a sand composed of rounded grains will vary between the two extremes, regardless of the diameters of the grains, provided the diameters are the same in the given sample. Samples of sand composed of well-rounded grains of nearly uniform diameter when compacted normally yield porosities of between 30 and 40 per cent. Increase in angularity of the grains increases the pore space over that exhibited by rounded grains of the same size. This principle has been used by Lamar to determine the angularity of the St. Peter sand of Illinois.[2] Mixing and compacting of sand of different sizes decreases the pore space since the finer grains tend to lodge in the spaces between the coarser grains. But in this condition the porosity resulting from very favorable assortment and uniform gradation is little below the theoretical minimum value, 29.95, for grains of uniform size arranged as compactly as possible,[3] a value nearly three times the average of the results of porosity determinations of the St. Peter sandstone. This comparison of the porosity of a sandstone with the porosity of compacted sand grains is possible

[1] Quoted by F. H. King, "Principles and Conditions of the Movements of Ground Water," *U.S. Geol. Surv., Nineteenth Ann. Rept.*, Part II (1899), pp. 207–18.

[2] J. E. Lamar, "Geology and Economic Resources of the St. Peter Sandstone of Illinois," *Ill. Geol. Surv., Bull. 53* (1928), pp. 148–52, and Table 12, p. 151.

[3] F. H. King, *op. cit.*, p. 216, Fig. 39.

since it has been demonstrated that clay and other cementing material are essentially absent from the sandstones.[1] But it may be open to question whether a sand artificially compacted can have its pore space reduced to the condition of an old sandstone that has long been buried and correspondingly subjected to compressive stress. Allowing, however, for prolonged compaction, there still remains too great a discrepancy between the porosity of St. Peter sandstone and the porosity of sand.

According to Melcher, the porosity of the Arkansas samples is rather low when compared with most of the Wilcox sand in the producing fields of Oklahoma, the producing zone of the Wilcox sand varying in porosity from about 8 to 37 per cent.[2]

GRAIN SIZE

Recent studies of St. Peter sand reveal a large variation in grain size of the sand. In discussing the results obtained in the study of St. Peter sand of Missouri, Dake concludes that "the factor of uniformity has been heretofore greatly overestimated in describing the St. Peter formation." And in comparing the results of tests of the St. Peter sand with results obtained from analyses of a large number of samples representing eight formations ranging in age from Cambrian to Tertiary, Dake states "the difference is entirely inappreciable either as to average or extreme range."[3] The work of Lamar indicates a similar absence of uniformity in grain size of the Illinois St. Peter sand.[4]

The wide range in grain size revealed in the analyses of Missouri and Illinois St. Peter sand is likewise characteristic of the Arkansas sand. Of fifty-four samples of St. Peter sand analyzed, none had grains with diameters as large as 0.032 inches, 12 per cent had diameters larger than 0.016 inches, 78 per cent between 0.016 inches and 0.005 inches, and only 10 per cent of the grains had diameters smaller

[1] *Ark. Geol. Surv., Bull. 4* (1930), pp. 70–77, 147–48, 157.

[2] A. F. Melcher, personal communication dated Tulsa, Oklahoma, November 14, 1930.

[3] C. L. Dake, "The Sand and Gravel Resources of Missouri," *Mo. Geol. Surv.*, 2d Ser., Vol. XV (1918), p. 127.

[4] J. E. Lamar, "Geologic and Economic Resources of the St. Peter Sandstone of Illinois," *Ill. Geol. Surv., Bull. 53* (1928), p. 148, Table 10.

than 0.005 inches. Nearly 1 per cent had diameters smaller than 0.003 inches.[1]

Analyses of Calico Rock and Kings River sandstones yielded similar results.[2]

Samples collected from the same horizon at closely adjacent localities, even from the same outcrop, may show considerable diversity in grain size when results of analyses are compared, but an adequate conception of the texture of any one of the sandstones for any particular locality or horizon may be obtained by averaging results of several analyses.

A comparison of the average results of a large number of mechanical analyses of St. Peter sand of Illinois, Missouri, and Arkansas clearly indicates the increasing fineness of the sand in proceeding southward in the Mississippi Valley.[3] This increase in fineness is attributed to greater attrition resulting from farther transportation from the original source of the sand in northern United States and southern Canada.

SHAPE OF THE GRAINS

During the progress of the investigation of the Ordovician sandstones of Arkansas for the Arkansas Geological Survey, three samples of St. Peter sand were studied by Brewster with particular reference to the various shapes the grains exhibit.[4] The study followed the procedure recommended by Trowbridge and Mortimore.[5] It was found that less than 3 per cent of the grains were rounded, and only 8 per cent fairly well rounded; slightly more than one-fourth (28 per cent) of the total number of grains were found to be subangular, and more than one-half, 61 per cent, were distinctly angular. These results departed so notably from the prevalent conception of well-rounded grains composing the St. Peter sandstone that five additional samples were subsequently studied to ascertain if the general results obtained in the first study would hold for a larger number of

[1] *Ark. Geol. Surv., Bull. 4* (1930), Table 5, opp. p. 28.

[2] *Ibid.*, Table 35, opp. p. 120; Table 52, p. 156.

[3] *Ibid.*, pp. 42–45.

[4] *Ibid.*, pp. 45–48.

[5] A. C. Trowbridge and M. E. Mortimore, "Correlation of Oil Sands by Sedimentary Analysis," *Econ. Geol.*, Vol. XX (1925), pp. 409–23.

samples and for additional localities.[1] The results of the study of the second set of samples were found to agree closely with the results obtained from the study of the first set of samples and to indicate that the St. Peter sandstone of Arkansas consists dominantly of angular grains possessing an infinite variety of shapes. Many grains have no rounded surfaces whatever; other grains have a part of their surfaces rounded. Rounded grains are very rarely round, but instead are oblong, bean-shaped, spindle-shaped, egg-shaped, or more rarely lens-shaped, or conical.

Preliminary to the study of the shape of the grains, each of the five samples was screened[2] to yield seven residues of successively finer grains, and 100 grains were arbitrarily selected from each residue for microscopic examination. In the five samples less than 3 per cent of the sand grains were found to be rounded, and slightly more than 14 per cent fairly well rounded; about one-fourth (23 per cent) of the total number of grains were subangular, and 60 per cent were angular.

With increasing fineness in grain size there is a corresponding decrease in rounding of the grains. Essentially all (97 per cent) of the rounded grains were found in the four coarser residues, grains having diameters greater than 0.0082 inches. Of the fairly well-rounded grains, 86 per cent were found in the four coarser residues. Subangular grains were found to be very evenly distributed through the coarser sizes, but their proportion declined rapidly in the three finer residues. Angularity, on the other hand, showed a constant increase with increasing fineness of grains; more than three-fourths of the grains (77 per cent) lodging on the three finest meshes were found to be angular.

[1] The five samples used as the basis for the study of the textural features described in this paper were collected as follows:

1. Piney Creek at Metalton, Carroll County, Eureka Springs quadrangle, Eureka Springs–Harrison Folio.
2. Marble City Falls, Newton County, Harrison quadrangle, Eureka Springs–Harrison Folio.
3. Bellefonte, Boone County, Harrison quadrangle, Eureka Springs–Harrison Folio.
4. Near top of Pilot Knob, Izard County, *Bull. 4, Ark. Geol. Surv.*
5. West of Big Flat 7.5 miles, Searcy County, *Bull. 4, Ark. Geol. Surv.*

[2] Tyler Standard sieves. Numbers 28, 35, 48, 65, 100, 150, and 200 were used. For sizes of grains lodging on each sieve see *Ark. Geol. Surv., Bull. 4* (1930), p. 26, Table 3.

Broadly generalizing on the basis of the results obtained, one out of four of the grains of the four coarser meshes (grain size 0.0082 inches +) is likely to be rounded or fairly well rounded; whereas only one out of twenty-one of the grains lodging on the three finest meshes (grain size 0.0082 inches −) is likely to be rounded or fairly well rounded.

DEVELOPMENT OF CRYSTAL FACES

The St. Peter sand grains of Arkansas exhibit a remarkable development of crystal faces. This feature is so conspicuous in representative samples that many of the grains resemble an aggregate of minute, more or less perfect quartz crystals. The crystal faces may be as clear and transparent as those developed on large quartz crystals familiar as laboratory and museum specimens, or they may be clouded due to delicate etching following their formation. Chipping and other evidences of abrasion are essentially absent.

Of 3,500 grains representative of five samples of St. Peter sandstone selected as typical of the formation, only about 10 per cent (340 grains) showed no crystal faces. On the other hand, nearly two-thirds of all the grains (66 per cent) had crystal faces developed on a part of the grain, and nearly one-fourth (23 per cent) had crystal faces forming most of the surface of each grain. One per cent of the grains had been transformed into quartz crystals.

The crystal forms developed on the sand grains are normally prismatic and rhombohedral. Rhombohedral faces often terminate the grains developing normal to the surfaces of sharp curvature, and prism faces are present about the central parts of the grains, developing tangential to surfaces of gentle curvature. Rhombohedral faces, however, may project from the medial surface of the grains, and some grains terminate in prisms which in turn are terminated with the rhombohedrons. Closely set prisms terminated with rhombohedrons may project from a part or all of the surface of the grain, presenting a drusy appearance under the microscope.

Crystal faces are not limited to grains of any particular size; but of the small proportion of grains showing no crystal faces, the coarser sizes predominate. On the other hand, the grains of larger sizes are also most likely to be complete quartz crystals. Grains with crystal

faces developed on the smaller part of their surfaces show a very uniform distribution through all sizes from coarsest to finest. Grains with crystal faces developed over the larger part of their surfaces show a similar distribution in the coarser sizes with a marked decrease in the finer sizes.

SECONDARY ENLARGEMENT

The textural features characterizing the St. Peter sandstone so far described are attributed chiefly to secondary enlargement. The low porosity, the large variation in grain size, the angularity, and the crystal faces present on most of the grains have resulted mainly from factors in operation since the deposition of the sand. Originally the grains were of much more nearly uniform size; they were rounded or fairly well rounded; crystal faces were absent except on some of the smallest grains representing survival from the original source of the sand; and the porosity of the sandstone was equivalent to that of sandstone consisting of rounded grains of nearly uniform size, roughly three times its present average porosity.

The variation in size of the grains as revealed in mechanical analyses, when compared with the original condition of the sand as determined by microscopic examination, is reflected chiefly in the very large residues lodging on the finer meshes. Microscopic examination of the residues of the finer meshes reveals an aggregate resembling finely crushed glass and consisting largely of angular fragments of secondary quartz broken off the larger grains during the collection of the samples and the screening of the sand, with a small proportion of original small grains, and a negligible proportion of fragments, slivers, and chips derived from the attrition of larger grains during and subsequent to deposition.

The precipitation of secondary quartz upon the originally rounded surfaces of the grains has resulted in the development of the crystal forms and faces characteristic of the majority of the grains and in the pronounced angularity that most of the grains exhibit. In many grains secondary enlargement has not terminated with the formation of secondary crystals and faces upon the original surfaces of the grains, but has proceeded with the development of additional crystals and faces upon the surfaces of the secondary quartz previously

deposited, thus forming crystals and faces of the second and even third generation. Frequently, several original grains have coalesced by the precipitation of silica, and the mass become covered with succeeding generations of secondary quartz crystals presenting the appearance of a delicate and intricate mat.

The extent of recrystallization varies with the locality where the samples were obtained. Samples collected at Marble City Falls in northern Newton County show the greatest degree of recrystalliza-

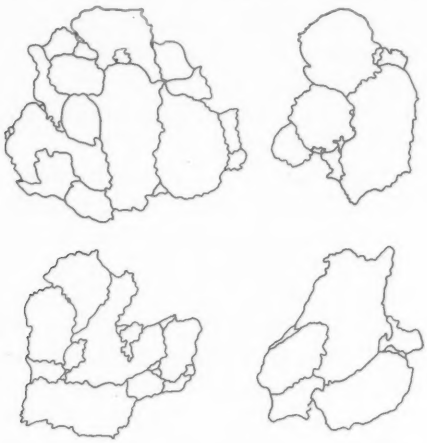

FIG. 1.—Camera lucida sketches of parts of thin sections showing angularity, closely knit fabric, and mutual relations of grains.

tion of all samples studied. One-fourth to one-third of the mass of the sample may consist of secondary silica. Many samples collected at this locality are virtually quartzitic in their resistance to crushing, secondary silica completely filling interstices between the grains and converting the rock into a coherent, non-porous mass of quartz.

OPTICAL CHARACTERS

Microscopic examination of thin sections of the St. Peter sandstone reveals a closely knit aggregate of angular quartz grains with mutually penetrating boundaries, as illustrated in Figure 1. That the angularity is due to deposition of secondary silica is readily de-

termined in the thin sections, since the original outlines of the grains can in most cases be detected as thin, concentric lines separating the quartz of the original grains from the bounding secondary quartz. The original outlines normally exhibit the rounded character of well-

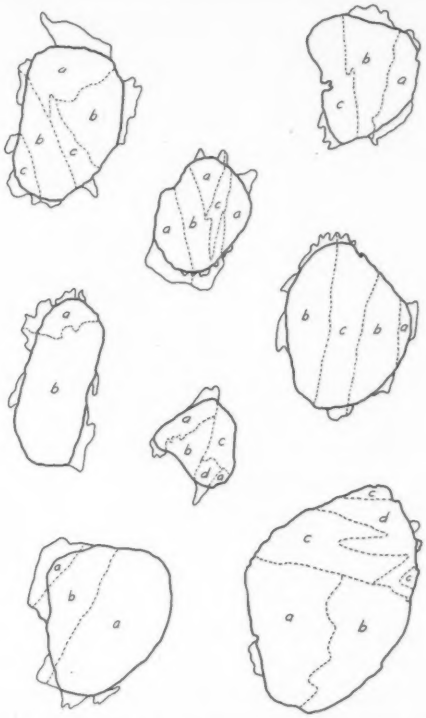

FIG. 2.—Camera lucida sketches under crossed nicols of single grains from thin sections showing extinction boundaries (dashed lines) and secondary quartz. Heavy line indicates original boundaries of grains; light line, boundaries of secondary quartz; *a*, *b*, etc., indicate crystallographic unity with simultaneous extinction.

worn sand grains. The relation of the secondary quartz to the originally rounded grains is illustrated in Figure 2.

Microscopic examination of individual sand grains indicates that many of the larger grains are not crystallographic units. To obtain quantitative results, eight thin sections of the sandstone were studied

with particular reference to the extinction, under crossed nicols, exhibited by the larger grains of the sections. Of a total of 780 grains, 465 were found to be crystal aggregates, two or more parts of each grain extinguishing differently, and 315 grains were found to be

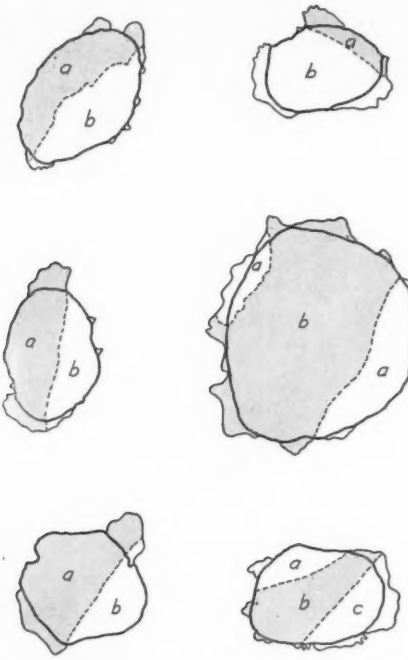

FIG. 3.—Camera lucida sketches under crossed nicols of single grains from thin sections showing optical continuity of secondary quartz with that part of the original grain to which it is attached. Heavy line indicates original boundaries of grains; light line, boundaries of secondary quartz; dashed lines, extinction boundaries; *a*, *b*, etc., crystallographic units.

crystal units. The optically component parts of the larger grains are illustrated in Figures 2 and 3. The smaller grains normally exhibit crystallographic unity. This may be expected for two reasons: many of these grains are crystals and parts of crystals broken off the original surfaces of the larger grains; many of the others are composed of

original quartz and are contemporaneous in origin with the other original grains of the sandstone, their small size favoring derivation from crystallographic units of the parent quartz mass.

The optical orientation of the secondary quartz agrees with that part of the original grain to which it is attached. The extinction boundaries of the original grain, therefore, transect without deviation the bounding secondary quartz. This relationship is illustrated in Figure 3.

Most of the grains are free from mineral and other inclusions. When present, the mineral inclusions rarely exceed two or three in number in the individual grains.

PITTING

Pitting is a characteristic feature of St. Peter sand grains. The phenomenon has been studied by Lamar in his investigation of the St. Peter sandstone of Illinois, and he has discussed the dimensions and the origin of the pits at some length.[1] In a preliminary study of three samples of the St. Peter sand selected as typical of the formation in widely separated localities, Brewster concluded that approximately one-third of the grains were pitted.[2] The present study involved a larger number of samples than Brewster studied, representing a larger area in the distribution of the sandstone. The grains of five samples were graded into seven sizes by screening, and 100 grains from each of the seven residues of each of the five samples were arbitrarily selected for binocular examination. Of the 3,500 grains, 60 per cent were found to be pitted. Pitting progressively decreases with increasing fineness of grain; nearly every grain of the three coarser sizes was pitted, more than half of the grains (54 per cent) of the two intermediate sizes were pitted, but in the minute grains of the two smallest sizes pitting was found to be much more rarely developed, averaging only 12 per cent of the total number of grains lodging on these fine meshes.

The number of pits varies on grains of similar sizes. Many of the larger grains have from five to twenty-five pits on their surfaces,

[1] *Ill. Geol. Surv., Bull. 53* (1928), pp. 47–49; and *Bull. Geol. Soc. Amer.*, Vol. XXXVIII (1927), pp. 459–68.

[2] *Ark. Geol. Surv., Bull. 4* (1930), pp. 55–57.

grains of intermediate size from five to fifteen pits, but in grains lodging on the three finest meshes the number of pits present is less than five. The shape of the grain has no relation to pitting. Pits are as typically developed in angular and subangular as in rounded grains. The size of the pits varies as widely as their number. Normally, many small pits are present, but some grains are indented with one to three pits occupying a large proportion of the surface exposed to view. In general, the smaller the grain, the smaller the pits; but grains of the smallest sizes may show a single pit occupying a large portion of the surface of the grain, although typically the pits of these small grains are very minute.

Normally, the distribution of the pits is uniform over the surface of the grain, and in many grains they are so closely spaced as to give the surface of the grain a rough, cavernous appearance under the binocular. In other grains the pits are widely separated. A few of the larger grains show pits only on part of the surface, a condition that is normal in pitted grains of the smaller sizes.

In shape the pits may be round, oblong, lunar, or angular. Angular pits are bounded by three, four, five, or six sides. In depth the pits may be so shallow as to be detected with difficulty, or they may penetrate to a distance of half of the radius of the grain.

In grains with pits widely spaced, secondary silica forms smooth crystal faces between the pits; but where they are closely spaced, the silica is usually developed as sharp, angular boundaries between adjacent pits. Pitting is almost as frequent in the secondary quartz as in the original surfaces of the grains.

Pitting has originated in several ways. It may result from solution at the points of contact of adjacent grains, one grain slowly penetrating the other or the grains mutually penetrating. If the solution of both grains is roughly equal, scars are formed; if the solution is unequal, shallow pits resembling lunar craters are formed.[1] Development of pits by penetrating sand grains is illustrated in Figure 4, *A*. More rarely pits are developed by deposition of secondary silica about the points of contact of adjacent grains. The floors of pits developed in this way are flush with the original surface of the grain. The relations are illustrated in Figure 4, *B*.

[1] J. E. Lamar, "New Facts Concerning the St. Peter Sandstone of Illinois," *Bull. Geol. Soc. Amer.*, Vol. XXXVIII (1927), pp. 467–68.

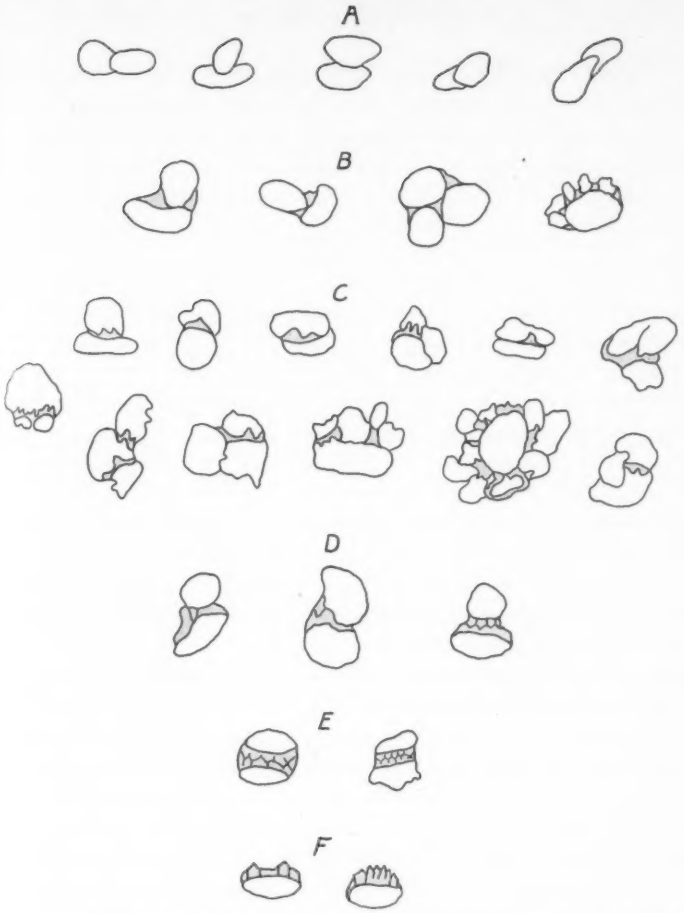

FIG. 4.—Origin of pitting of the grains. *A*, *E*, and *F* diagrammatic; *B*, *C*, *D*, sketched with camera lucida.

A—Pitting resulting from penetration of one grain by another.

B—Pitting resulting from deposition of secondary silica about points of contact of adjacent grains.

C—Pitting resulting from penetration of original grains by crystals of secondary quartz developed on the surfaces of adjacent grains.

D—Pitting resulting from penetration of secondary crusts by crystals of secondary quartz from neighboring grains.

E—Pitting resulting from intergrowth of secondary crystals from crusts coating adjacent grains.

F—Pitting resulting from secondary crystals arising through and from secondary quartz crusts.

The majority of the pits, however, appear to have originated in other ways. Pitting very frequently results from penetration of original grains by crystals of secondary quartz developed on the surfaces of adjacent grains. In breaking apart the grains, the crystals normally are detached from the cavities they have formed in the original surfaces of adjacent grains; much more rarely they are broken off flush with the original surface of the penetrated grain, the rhombohedral termination remaining embedded in the grain penetrated. This relationship, illustrated in Figure 4, *C*, involves a molecular rearrangement of the molecules of the grain penetrated to form the termination of the penetrating secondary crystal. In thin sections under crossed nicols the termination of the secondary crystal embedded in the adjacent grain extinguishes at the same time as the remainder of the crystal and its associated secondary quartz, but differently from the quartz composing that part of the grain penetrated by the secondary crystal. Pits so developed are normally angular.

The penetration of secondary crusts coating the original surfaces of the grains by crystals of secondary quartz arising from neighboring grains is another cause of pitting. In this case the pits are revealed as depressions with angular outlines in the secondary quartz coating when the grains are separated. The relationship is illustrated in Figure 4, *D*. A similar relationship, Figure 4, *E*, results from intergrowth of secondary crystals arising from crusts coating adjacent grains. In the separation of the grains the quartz crystals tend to separate without fracture, leaving angular depressions marking the terminations of the crystals from the neighboring grain. In thin sections under crossed nicols the crystals extinguish together with the crust from which they arise, but differently from the adjoining crystals originating in the crust of the neighboring grain.

Pitting also results from crystals arising through and from secondary crusts, as illustrated in Figure 4, *F*. The breaking of these crystals in handling the grains leaves angular depressions, marking the place of origin of the secondary crystals.

It thus appears that pitting of the grains may originate in six different ways, but in only two cases (*A* and *C*, Fig. 4) are the pits indented into the original surfaces of the grains. The pits developed

according to the first two methods (*A* and *B*, Fig. 4) are rounded, oblong, or lunar; but when developed according to the other methods, they are angular, with three, four, five, or six sides, depending on the geometrical forms of the penetrating crystals as well as on the completeness of development of their crystal faces.

FROSTING

The recent investigation of the St. Peter sand of Arkansas with especial reference to frosting indicates that the conception of universal frosting of the grains is only partly correct, even when restricted to the coarser grains of the sandstone.[1] In general, rounded grains are almost without exception completely frosted, but the grains with angular outlines are either not frosted or only partly frosted. Most of the finer grains are unfrosted.

The present investigation was based on a detailed study of five samples, each of which was screened into seven residues of increasing fineness, 100 grains being arbitrarily selected from each residue. Of the 3,500 grains studied, 35 per cent were found to have more than three-fourths of the surface of each grain frosted, 26 per cent of the grains showed frosting on a part of the surface, and 39 per cent of the grains showed no frosting. About four-fifths (83 per cent) of the grains lodging on the four coarser screens were largely or partly frosted. Frosting declines rapidly with decrease in grain size, only 31 per cent of the grains lodging on the three finest screens were found to be frosted, with but one grain in six of the residue of finest grains frosted. Since the diameters of these minute grains are less than 0.0041 inches, their frosting indicates the ability of the wind to abrade surfaces of grains of almost microscopic dimensions.

The proportion of frosted grains varies considerably in different samples, but the average results obtained using different sets of samples indicate a marked uniformity in this textural feature prevalent throughout the formation.

The study of frosting of St. Peter sand grains of representative samples indicates that the surfaces of the original grains of the sandstone had been generally frosted by wind action, with the exception of some of the smallest grains. The precipitation of silica on the sur-

[1] *Ark. Geol. Surv., Bull. 4* (1930), pp. 60–63.

faces of the grains subsequent to the deposition of the sandstone has largely or partly covered the frosted surfaces. In many grains the deposition of secondary quartz has been carried to the extent of concealing the originally frosted surfaces except at the points of contact of original grains.

ETCHING

During the progress of the study of the frosting of the St. Peter sand grains it became apparent that the origin of the rough surfaces of the grains was due not only to wind abrasion but also to solvent action of underground water subsequent to the deposition of the sand. The effect of the solvent action may be described as "etching," reserving the term "frosting" for the effect of the wind. Although solvent action affecting the surfaces of the grains produced a finer and shallower texture than the texture resulting from the action of the wind, yet it was not found to be possible always to distinguish frosting due to wind abrasion from etching due to solution. This was particularly true of the coarser grains, where frosting was so pronounced that the subsequent etching, if present, was not discernible. In a quantitative study of several hundred grains of all sizes relative to the extent of etching, it was found that on 67 per cent of the grains etching could be distinguished, and that etching increases with decrease in grain size, 50 per cent of the coarsest grains, 75 per cent of the medium-sized grains, and two-thirds of the smallest grains having been etched.

Not only have the original surfaces of the grains been etched where exposed to the action of underground water, but the surfaces of secondary quartz are likewise etched, and edges and corners of secondary quartz crystals may be clouded and rounded. Conchoidal surfaces present on many smaller grains and representing the place of former attachment to larger grains are free from etching.

Etching of the secondary silica is, however, by no means universal. Many faces of secondary origin are free from etching and are perfectly clear and transparent, and many angles are sharp and clear, composed of transparent quartz. When more than one generation of secondary quartz faces and crystals is present, the latest generation has often escaped etching, but previous generations normally show the effects of etching.

Many pits are etched. Pits formed by penetrating grains and by

secondary quartz crystals penetrating the original surfaces and the secondary coatings of adjacent grains are normally etched by the solvent action involved in the penetration. The etching has no obvious relation to the size or to the shape of the pits thus developed; angular pits as well as rounded pits, and deep pits as well as shallow, are etched. With increasing fineness in the size of the grains the etching of the pits becomes increasingly imperceptible, and is not apparent in many of the minute pits present in the grains composing the residues of the finest screens.

SOURCE OF THE SECONDARY SILICA

The silica involved in the marked secondary enlargement of the grains originated largely by solution in the zone of weathering. That this zone does not furnish all of the silica is indicated by the widespread etching of the surfaces of the grains and of secondary quartz previously deposited by circulating waters. The original porosity of the formation aided in the downward penetration of surface water, and hence was an important factor in secondary enlargement. It follows obviously that secondary enlargement should be most complete where water circulation was most active and where the circulating water was most amply supplied with dissolved silica. Favorable situations would be expected near outcrops, in the upper parts of the formation under thin cover, and along originally more porous layers. The small porosities of samples 1–10, Table I, collected near the outcrop, as compared with the relatively large porosities of the samples collected underground under thick cover at Guion (samples 11 and 12, Table I), apparently support this conclusion. Where the formation is deeply buried and overlain with relatively impervious strata, secondary enlargement may be expected to be less extensively developed. This conclusion supports the statement of Melcher that the porosity of the Arkansas samples is rather low when compared with most of the Wilcox sand in the producing fields of Oklahoma.[1]

A possible relationship of succeeding generations of secondary quartz to old land surfaces is suggested since several unconformities are present in the stratigraphic sequence above the St. Peter sandstone in northern Arkansas. It is possible that the earlier generations of secondary quartz crystals and faces found on the original surfaces of many of the sand grains may have been formed in part or wholly

[1] *Op. cit.*

by precipitation of silica carried downward after solution in the zone of weathering of these old land surfaces. This would associate the last generation of secondary quartz crystals, chiefly unetched, with solution in the present zone of weathering, and reprecipitation of the silica under conditions essentially as now existing.

MAJOR EFFECTS OF SECONDARY ENLARGEMENT

The extent to which secondary enlargement has progressed determines the degree of coherence of the sandstone. In many places the sandstone is so friable as to be readily disintegrated by rubbing fragments between the fingers. In other places the sandstone may be almost quartzitic in its resistance to abrasion. A layer may be friable in one place and within a few feet be thoroughly indurated; a resistant layer may be overlain and underlain by friable layers. These differences in resistance are attributable to the extent of secondary enlargement of the grains. Where the process has gone to completion, the rock is essentially a quartzite, although usually yielding by fracture of the secondary quartz rather than across the original grains. This explanation of the coherence of the sandstone neglects entirely the importance of "cements" which, as many chemical analyses indicate, are either absent or present in such negligible amount as to possess no efficacy in binding the grains together.[1]

Obviously the extent to which secondary enlargement has taken place in any locality will determine the capacity of the sandstone as a reservoir for water, or oil, in that locality. This capacity, therefore, would seem to be determined by depth of burial of the sandstone and porosity of overlying rocks, with presence or absence of unconformity immediately above the sandstone.

"Case hardening" of the sandstone to a depth from a fraction of an inch to a few inches is sometimes found in steep faces on slopes. In such situations the silica has been carried from the soil above down the face of the sandstone and deposited between the grains, or it has been precipitated during evaporation of water emerging from the sandstone beds.

CONCLUSIONS

The porosity of the St. Peter sandstone of Arkansas is low, averaging but 10.2 per cent for twelve samples. Samples collected near

[1] *Ark. Geol. Surv., Bull. 4* (1930), pp. 70–77.

the outcrop have a lower porosity than samples collected underground at a considerable distance from the outcrop and below the surface. The porosity is also low when compared with the porosity of well-cuttings from the producing horizon of the Wilcox sand of Oklahoma.

The results of many mechanical analyses unmistakably indicate an absence of uniformity in the size of the grains of the St. Peter sand. The average grain size may vary notably in samples collected in closely adjacent localities. A comparison of the average results of analyses of the St. Peter sand collected in Illinois, Missouri, and Arkansas clearly indicates the increasing fineness of the sand in proceeding southward in the Mississippi Valley, due to greater attrition resulting from farther transportation from the original source of the sand.

Angularity is characteristic of the St. Peter grains of Arkansas; less than 3 per cent were found to be rounded, slightly more than 14 per cent fairly well rounded, 23 per cent subangular, and 60 per cent were angular. Angularity increases with decrease in grain size.

The St. Peter sand grains exhibit a remarkable development of crystal faces which bound the original surfaces of the grains or rise normal to the original surfaces as rhombohedrons or prisms with rhombohedral terminations. Only 10 per cent of the grains showed no crystal faces on their surfaces, and 1 per cent had been transformed into quartz crystals.

The low porosity, the large variation in grain size, the angularity, and the crystal faces present on most of the grains have resulted chiefly from the precipitation of quartz upon the originally rounded surfaces of the grains forming one or more generations of secondary quartz crystals and faces. Originally the grains were much more nearly uniform in size, and rounded or fairly well rounded; crystal faces were rarely present; and the porosity of the sandstone was appreciably larger than its present porosity.

Microscopic examination of thin sections of the sandstone reveals an aggregate of angular quartz grains consisting of secondary quartz with irregular outlines coating the rounded original grains. The majority of the larger grains consist of two or more parts optically, the secondary quartz extinguishing with that part of the grain to

which it is attached. The smaller grains are for the most part crystallographic units.

Pitting is characteristic of the sand grains, 60 per cent of the grains having pits. The number of pits vary from less than five on small grains to twenty or more on large grains. Pits may be round, oblong, lunar, or angular, small or large, so closely spaced as to give the surface of the grain a cavernous appearance, or widely separated. Secondary silica developed as angular boundaries or smooth faces bounds the pits in many grains. Pitting has resulted from solution at points of contact of adjacent grains, from deposition of silica about points of contact, from penetration of original grains by crystals of secondary quartz arising from adjacent grains, from penetration of secondary crusts coating original grains by crystals of secondary quartz from neighboring grains, from intergrowth of secondary crystals from crusts coating adjacent grains, and from breaking crystals arising through and from secondary crusts in separating grains.

Microscopic examination indicates that approximately 61 per cent of the sand grains of the samples studied are largely or partly frosted. Originally the grains, except some of the smallest, were generally frosted. The precipitation of silica on the surfaces of the grains subsequent to the deposition of the sandstone has completely or partly covered the frosted surfaces.

The surfaces of the majority of the grains have been etched by the solvent action of underground water, etching affecting not only the original surfaces but also the surfaces of secondary crystals and faces. Many of the pits are also etched.

The origin of the secondary silica was primarily in the present and in former zones of weathering now represented by unconformities, and secondarily from etching of the surfaces of the original grains and secondary quartz previously deposited on the original grains. Consequently, secondary enlargement is greatest near outcrops, in the originally more porous parts of the sandstone, and in the upper parts of the formation under thin cover. The degree of coherence of the sandstone is determined by the extent to which secondary enlargement has progressed. The capacity of the sandstone as a reservoir for oil or for water is also determined by the extent of secondary enlargement.

IGNEOUS ROCKS IN THE BARABOO DISTRICT, WISCONSIN

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ABSTRACT

A restudy, with more ample descriptions than previously published. New interpretations are that the fragmental rhyolite at Alloa is a true flow breccia and not a basal phase of the Baraboo quartzite; that the sheared rhyolite at the Lower Narrows of the Baraboo River is older than the quartzite; that the so-called granite in Merrimac Township is flow rhyolite; and that evidence is lacking to substantiate the idea that the Otter Creek granite is intrusive into the Baraboo quartzite.

INTRODUCTION[1]

Igneous rocks of pre-Cambrian age have been recognized by various writers on the geology of the Baraboo district of south central Wisconsin. The most recent reports are those of Samuel Weidman in 1904[2] and W. C. Alden in 1918.[3] The discovery by the writer of water-laid tuff in the region in the spring of 1929 led to a study of all the igneous outcrops and as none of the previous reports has been devoted primarily to the igneous rocks and as some localities have not yet been adequately described, this article is thought justified, although, in part, it is a more complete description of material already in the literature, in particular, in the two reports mentioned above.

GENERAL GEOLOGY OF THE REGION

In the sketch map in Figure 1, the general geology of the Baraboo district is shown. An east-west, canoe-shaped syncline, or synclinorium, is outlined by dissected ridges of quartzite, presumably of Middle Huronian age, conformably overlain by Seeley slate and Freedom dolomite. The last two formations do not outcrop at the

[1] The helpful criticism of Professor U. S. Grant in reading the manuscript and in the microscopic study is gratefully acknowledged. Thanks are also expressed to Messrs. John Huddle, Raymond Sullivan, and Edward Finefield for assistance in the field work.

[2] Samuel Weidman, "The Baraboo Iron-Bearing District of Wisconsin," *Wis. Geol. and Nat. Hist. Surv.*, Vol. XIII (1904).

[3] W. C. Alden, "The Quaternary Geology of Southeastern Wisconsin," *U.S. Geol. Surv. Prof. Paper 106* (1918).

surface. The lower flanks of the quartzite ridges are covered with horizontally lying Cambrian (Potsdam) sandstone. Small remnants of later formations are not shown on the sketch map. Dips on the north flank approach verticality and on the south flank vary from 10° to 35°. The pre-Cambrian rocks occur just outside the borders

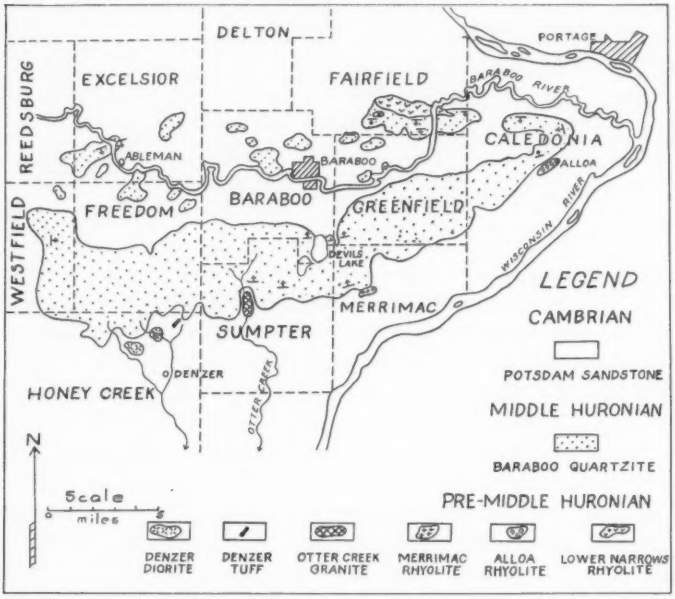

FIG. 1.—Sketch map of the Baraboo, Wisconsin, district showing location of the igneous rocks.

of the syncline and, with the possible exception of the Otter Creek granite, represent the pre-Middle Huronian floor upon which the quartzite was deposited.

DISTRIBUTION OF THE IGNEOUS ROCKS

Igneous rock is known to outcrop in at least seven different localities as follows: (1) rhyolite flow and breccia on the north flank of the syncline on both sides of the Lower Narrows of the Baraboo River in Secs. 20, 21, 22, and 23, T. 12 N., R. 7 E.; (2) flow rhyolite

and breccia near Alloa on the southeast flank of the syncline in Sec. 3, T. 11 N., R. 8 E.; (3) flow rhyolite on the south flank of the syncline near Merrimac in Sec. 32, T. 11 N., R. 7 E.; (4) granite in the upper valley of Otter Creek, Secs. 32 and 33, T. 11 N., R. 6 E.; (5) water-laid tuff northeast of Denzer in Sec. 11, T. 10 N., R. 5 E.; and (6 and 7) two areas of diorite northwest and north of Denzer in Secs. 9 and 10, T. 10 N., R. 5 E. The last four outcrops are on the south flank of the syncline.

LOWER NARROWS RHYOLITE

LOCATION AND FIELD RELATIONS

The rhyolite, exhibiting all the features of a flow, extends along the base of the north quartzite ridge of the syncline, on both sides of the Lower Narrows of the Baraboo River. Outcrops appear to be continuous from the center of the north boundary of Sec. 20 to the center of the east boundary of Sec. 32, T. 12 N., R. 7 E., a distance of $3\frac{1}{2}$ miles. The rhyolite covers nearly all of the NE. $\frac{1}{4}$ of Sec. 21 with a maximum width of more than $\frac{1}{2}$ mile, but in general it forms a belt less than $\frac{1}{4}$ mile wide. The most accessible exposures are a short distance east of the Lower Narrows south of the road, where the bare, glaciated ledges of rock extend from the road level for nearly $\frac{1}{8}$ mile to the south. The rhyolite area west of the river, while much larger and showing numerous outcrops, is covered with forest and brush, and continuous tracing is difficult.

Between the rhyolite and the quartzite which forms the main mass of the ridge there is everywhere a covered area, usually a depression, and at no place is the rhyolite exposed close enough to the quartzite to determine definitely the contact relations. A schistose phase of the igneous rock occurs along the southern border of the rhyolite in sections 20 and 21. Weidman states that this is "generally if not always near the contact of the overlying pre-Cambrian quartzite or conglomerate and may in some cases contain some sedimentary rock."[1] No specimens of the typically sericitic, schistose rhyolite under the microscope show any evidence of a sedimentary origin. Adjacent to the schistose rhyolite and apparently gradational from it is a fragmental phase which Weidman described as a

[1] *Op. cit.*, p. 15.

"volcanic breccia."[1] In a later report he interpreted it as part of the basal quartzite because of the presence of "seams made up of stratified water-deposited material, such as rounded pebbles of the rhyolite and schist and small grains of quartz."[2] The fragmental rock is composed of sub-rounded, lens-shaped fragments of rhyolite and feldspar in a schistose matrix. It has the appearance of an intensely sheared, fragmental rock, possibly of aqueous origin. In no place was the rock found to grade into the quartzite formation. The extreme dynamic metamorphism of the rock, its schistosity being much greater than any phase of the basal quartzite elsewhere, and its apparent gradation into the old, sheared rhyolite which in turn grades without break into the less altered rhyolite, suggest that the fragmental rock is part of the pre-Middle Huronian basement rather than a basal phase of the Baraboo quartzite.

A small area of dense, nearly black rhyolite occurs on the top of the quartzite ridge near the center of the eastern boundary of Sec. 20, T. 12 N., R. 7 E. Quartzite outcrops between this and the main mass of the igneous rock to the north. Another small area of black rhyolite occurs a short distance to the south in the old road. The quartzite nearest the rhyolite outcrops shows no trace of a basal conglomerate. The rhyolite may possibly represent irregular summits on a pre-Middle Huronian surface before the invasion of the sea in which the quartzite was deposited, or shearing movements during the formation of the syncline may have caused a slipping of younger quartzite outward from the center of the fold over older quartzite and the irregular surface of the rhyolite.

The main mass of the Lower Narrows rhyolite is a dark to reddish gray rock, varying in places to a lighter red. On some of the smooth, glaciated ledges numerous dark lenses from a fraction of an inch to several inches long suggest flowage and mixing of slightly different colored lavas. There are also a few apparent inclusions sub-rounded to angular, of a light red rhyolite. The rock has a dense, stony groundmass in which many small phenocrysts of reddish feldspar are recognized by their reflecting cleavage faces. Quartz phenocrysts, if present, are extremely rare, and under the hand lens the rock appears more like a trachyte or andesite than a rhyolite.

[1] *Bull. Univ. of Wis.*, Vol. I, No. 2 (1895), pp. 44–46.

[2] *Wis. Geol. and Nat. Hist. Surv.*, Vol. XIII (1904), p. 26.

The schistose phase of the rhyolite is distinctly sericitic in composition. It is light gray in color, exhibits a pronounced schistose structure, and is much softer than the main mass of the rhyolite. It breaks along shear planes and gives a powdery fracture in contrast to the brittle, sharp fracture of the less altered rock. Reddish spots in the schist have irregular outlines and are apparently altered feldspars.

The rhyolite is cut by complex systems of quartz veins from paper thinness to several inches in width. Many have an eastwest orientation. Other areas are shot through with short, irregular lenses of quartz which appear to be cavity fillings. The rock, except in its most schistose phase, has all the appearance of a devitrified flow or aporhyolite, and proof of the devitrification is seen under the microscope.

MICROSCOPIC CHARACTER

Flow lines, spherulitic structures, and the patchy groundmass characteristic of devitrification are prominent features of the rhyolite in thin sections. Feldspar phenocrysts are scattered throughout a completely recrystallized matrix of feldspar, quartz, sericite, carbonate, iron oxide, and pyrite. The feldspar phenocrysts are in all cases fractured or badly shattered and pulled apart. The less altered grains show extinction angles and refraction of oligoclase. There is much microperthite, some of which appears to be clearly replacing the older plagioclase. Sericitization is the most common form of alteration, the sericite filling cracks in the phenocrysts and in some cases entirely replacing them. A small amount of chlorite is present and carbonate is abundantly scattered through the phenocrysts and groundmass alike.

Quartz is prominent in all sections. It occurs as small interlocking grains in the recrystallized groundmass, in irregular aggregates, and in stringers or veins replacing other material. In no instance was quartz, as a definitely primary phenocryst, recognized. Drop-like areas occur as replacements of spherulitic structures and in small cavity fillings. In every case these show under crossed nicols a mosaic of several grains, differently oriented. What appears to be secondary infiltrations replacing chain spherulites and in irregular veinlets are extremely common.

The spherulites are, for the most part, considerably altered and

more or less obliterated by recrystallization, but traces of them are found in most sections. In ordinary light they are scarcely perceptible except as rounded centers and lenses about which flow lines are sinuously curved. Under crossed nicols the radiating structures are apparent. The fluxion structure is accentuated by the development of sericite along the lines of flow. Besides the spherulitic centers, the flow lines curve also about the feldspar phenocrysts and mosaic lenses of quartz, suggestive of the spherutaxitic structure of the South Mountain aporhyolites.[1] Perlitic partings are suggested in a few rounded areas.

In certain sections there is a resemblance to sedimentary textures in the fragmentation of the feldspar and the not inconsiderable amount of infiltrated quartz, replacing both phenocrysts and groundmass; however, the matrix is always that of a devitrified flow. Small feldspar crystals in the groundmass show rounded corners in a patchy matrix of elongated microlites of feldspar and irregular, interlocking areas of quartz. Scattered grains of pyrite and magnetite are common throughout. In places, numerous globulites and cumulites of the iron oxide accentuate the flow lines. A few grains of zircon are present. Secondary biotite is rare but occurs in small flakes associated with chlorite. By far the most common secondary products are sericite and carbonate. Fluorite was observed in a single section.

Weidman[2] gives two analyses of the rhyolite as follows:

SiO_2	71.24	73.00
Al_2O_3	12.20	15.61
Fe_2O_3	1.71	.....
FeO	5.44	1.95
MnO	0.97	.....
CaO	.98	0.79
MgO	0.13	.....
K_2O	1.86	0.88
Na_2O	4.29	4.95
SO_3	....	0.76
H_2O	0.81	1.06
	99.63	99.00

[1] Florence Bascom, "The Ancient Volcanic Rocks of South Mountain, Pennsylvania," *U.S. Geol. Surv., Bull. 136* (1896), pp. 42–63.

[2] *Op. cit.*, p. 16.

While the analyses indicate rhyolitic composition, it is difficult to know how much of the silica is due to infiltration. The rarity of definitely recognizable quartz phenocrysts is also suggestive that the magma may have been less acidic than the analyses show.

In the intensely sheared, fragmental rock (Fig. 2) associated with the sheared rhyolite, cataclastic structures are pronounced. Broken feldspar, lenses, and eyes of rhyolite, and in rare cases angular

FIG. 2.—Photomicrograph of sheared, fragmental rock from Lower Narrows area. With analyzer, ×50.

quartz fragments, are surrounded by a fibrous matrix of feldspar and quartz not unlike the devitrified aporhyolite of the flows. The large feldspar fragments are of microperthite and oligoclase, the latter predominant. Elongated lenses exhibit mortar-structures with small grains of quartz in a mesh of altered rhyolitic material. Schistose flowage is characteristic, and lamellae of sericite and chlorite curve about the larger fragments of minerals and rock. The rock may possibly represent a sheared conglomerate from decomposed rhyolite, but no definite evidence of an aqueous origin was found in any of the specimens studied. In view of this lack of evi-

dence it seems more reasonable to assume that the rock was originally a volcanic tuff or breccia or even a rhyolite flow which was subjected to brecciation and recrystallization in the zone of flow.

In either case the intense shearing and high degree of recrystallization to which the rock has been subjected is in marked contrast to the nearest outcrops of the Baraboo quartzite. The evidence both in the field relations and in microscopic sections suggests a pre-Baraboo origin. Whether it was a true flow breccia or a volcanic breccia deposited in water, it is believed to represent the floor upon which the Baraboo quartzite was deposited and not a basal phase of this formation.

ALLOA RHYOLITE

LOCATION AND FIELD RELATIONS

The Alloa rhyolite is exposed on both sides of an elliptical mound on the Shanks' farm just northeast of the United Presbyterian Church, Caledonia Township, in the NE. $\frac{1}{4}$ of NE. $\frac{1}{4}$ of Sec. 3, T. 11 N., R. 8 E. The mound trends northeast and bare rock extends along either side for about 50 to 75 feet. The outcrops are separated by a covered area along the crest, but the entire mound of 300 by 75 feet is evidently of rhyolite. Small isolated ledges occur in the valley between the mound and the quartzite bluff, less than $\frac{1}{8}$ mile to the north.

The smooth glaciated surfaces show a large number of fragments of flow rhyolite in a slightly darker matrix of the same rock. The outcrop is ash-gray in color and weathering has etched out the flow lines in both the fragments and the groundmass, so that the ledges now present a striking appearance of a flow breccia with sharply angular fragments oriented in all directions (Fig. 3). The fragments vary from small grains up to several feet. Not all of them are angular but in places the rock has the appearance of a conglomerate or agglomerate with sub-rounded pebbles (Fig. 4). Along the south ledge of the mound the rhyolite grades into a more massive rock with dark bands which, in the field, suggest bedding, but under the microscope fail to show any evidence of a sedimentary origin. Weidman mentions that "thin seams of slate and arkose are stratified with the coarser conglomerate"[1] and concludes that most of the mound is

[1] *Op. cit.*, p. 27.

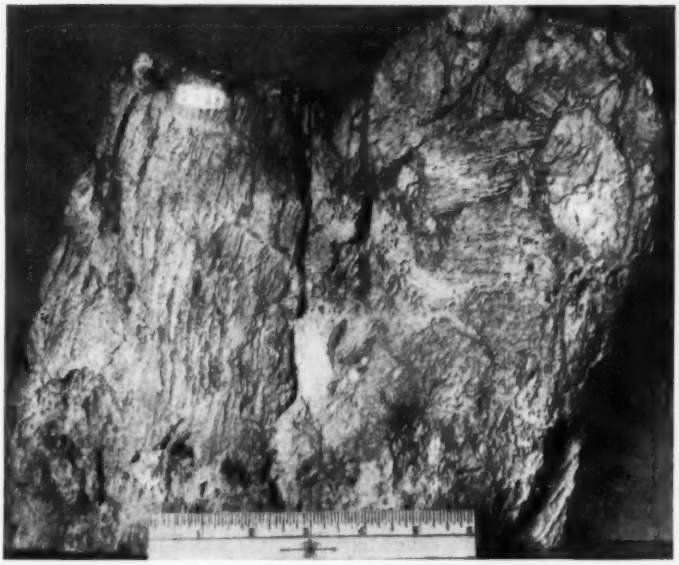

FIG. 3.—Flow breccia from the Alloa area showing angular fragments of rhyolite with flow lines etched out by weathering.

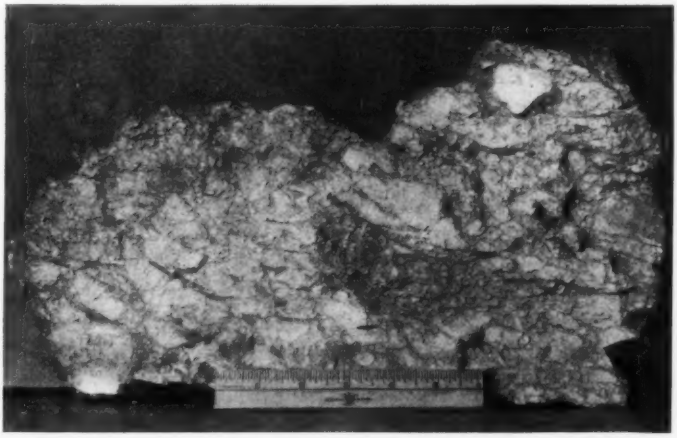

FIG. 4.—Flow breccia from the Alloa area showing subrounded fragments of rhyolite in a matrix of rhyolite.

basal conglomerate of the Baraboo quartzite. No quartzite, however, has been observed overlying the rhyolite and at no place was a gradation found between the rhyolite breccia and quartzite. The rhyolite is believed to belong to the old floor upon which the Middle Huronian quartzite was deposited.

MICROSCOPIC CHARACTER

The writer was inclined to consider the Alloa outcrop a volcanic breccia or agglomerate, possibly deposited in water, especially as the rhyolite-like rock in the vicinity of Denzer appears to be clearly a water-laid tuff. Microscopic study, however, of many sections of the Alloa outcrop fails to reveal any clear evidence of a sedimentary origin. The very dense, slate-like rock with dark bands suggestive of bedding shows in thin sections as a devitrified felsite, the dark bands being due to concentrations of sericite, chlorite, and carbonate. The rock is completely recrystallized to a fine matrix of interlocking quartz and feldspar with a few phenocrysts of oligoclase feldspar. The rounded corners of the larger feldspars and the patchy groundmass are typical here as in other portions of the rhyolite flows (Fig. 5).

Thin sections of the rhyolite, most resembling conglomerate in the field outcrops, are characterized by flow lines curving about shattered and angular fragments of feldspar, and around lenses of devitrified felsite and porphyritic rhyolite. These lenses are commonly of darker rock due to concentrations of small magnetite grains. The iron oxide crystallites drawn out along the lines of flow accentuate the fluxion structure. The fragments show some tendency toward a parallel orientation of their longer axes. Sericite, carbonate, and pyrite are common to all portions of the rock (Fig. 6).

The rhyolite containing the sharply angular fragments differ very little under the microscope from that containing the more rounded particles. Both contain feldspar and rhyolite fragments in a recrystallized matrix in which flow lines are well developed. The rounding in no case seems to be due to water action but has the appearance of squeezed lenses of rock such as might be expected in a flow breccia. Certain parts of the rock are decidedly more basic than others, as evidenced by thickly scattered grains of magnetite from the size of small cubes to fine dust. In places an alteration of

FIG. 5.—Photomicrograph of dense facies of the Alloa rhyolite showing patchy groundmass due to devitrification. With analyzer, ×50.

FIG. 6.—Photomicrograph of fragmental facies of the Alloa rhyolite. With analyzer, ×50.

the magnetite to hematite imparts a decidedly reddish color to the entire section. In the more basic portions are a few areas of chlorite, magnetite, and carbonate which suggest alteration residues from a former pyribole.

The absence of definitely water-rounded pebbles, aqueous sorting, and of any foreign particles other than material of the rhyolite itself, together with the pronouncedly angular fragments of flow rhyolite in a matrix of the same rock, suggest origin from a flow in which the more quickly cooled surface was broken by movement of the still mobile lava beneath; and that these fragments of the crust, oriented in various directions, were embedded in the lava to form a true flow breccia.

In the rhyolite nearer to the quartzite bluff to the north, the fragmental character is absent. The rock has a slightly coarser matrix than usual and there are fewer phenocrysts. Areas of chlorite and magnetite suggest the remains of altered pyribole. Such a rock might represent a deeper portion of the same flow which contains the breccia of the higher ledges.

MERRIMAC RHYOLITE

LOCATION AND FIELD RELATIONS

Alden[1] mentions a small area of granite in Merrimac Township near the center of the north boundary of Sec. 32, T. 11 N., R. 7 E. The rock is rhyolite similar in many respects to the denser phases of the Lower Narrows and Alloa outcrops. It extends in broken ledges east and west along the south base of the quartzite ridge called Devil's Nose, forming a part of the south limb of the anticline. The outcrop is nearly 300 feet long and 30–40 feet wide. In general, the rock is dark red to reddish gray, of extremely dense to stony texture. In places the phenocrysts of feldspar are small, widely scattered, and show dull, altered surfaces instead of bright cleavage faces. In other ledges a porphyritic texture is well developed with red feldspar up to $\frac{1}{4}$ inch in diameter. The inconspicuousness of the feldspar and the reddish color make the rock similar in field appearance to the quartzite which outcrops in the cliffs a few feet to the north. Nowhere is a contact between the two formations exposed, nor is there

[1] W. C. Alden, *op. cit.*, p. 59.

any evidence here of a conglomeratic phase in the quartzite. The rhyolite shows neither a schistose phase similar to the Lower Narrows rhyolite, nor a breccia phase as at Alloa. The nearby quartzite cliff is fractured and sheared in many places but in no way comparable to the intense shearing of the igneous rock at the Lower Narrows. If younger quartzite was sheared out from the center of the fold here, the movement would have been to the south over the

FIG. 7.—Photomicrograph of porphyritic rhyolite from the Merrimac area. With analyzer, ×50.

rhyolite, in the opposite direction to the movement at the Lower Narrows.

MICROSCOPIC CHARACTER

Under the microscope, the rhyolite differs chiefly from the Alloa outcrop in containing more numerous phenocrysts and in lacking the fluxion and brecciated structures (Fig. 7). The phenocrysts are for the most part oligoclase and in practically all cases show a high degree of fracturing, saussuritization, and sericitization. Quartz as a primary phenocryst is not evident, although it is abundant in the devitrified, felsitic matrix. Irregular stringers of quartz throughout

the rock resolve under crossed nicols into aggregates of differently oriented grains and appear to be secondary. Many of the feldspars are partially replaced by the quartz mosaics, and, in places, the quartz veinlets make up a considerable portion of the rock. Thickly speckled areas of magnetite suggest the presence of former ferromagnesian phenocrysts, but outlines of the original mineral were not recognized. Much of the magnetite is altered to hematite.

The rock appears in all respects a devitrified porphyry or aporhyolite into which a considerable amount of secondary quartz has been infiltrated.

WATER-LAID TUFF NORTHEAST OF DENZER

LOCATION AND FIELD RELATIONS

The tuff is exposed in a ledge nearly 200 feet long and 5–20 feet wide on the north bank of a small stream in the SE. $\frac{1}{4}$ of Sec. 11, T. 10 N., R. 5 E., about $1\frac{1}{2}$ miles northeast of Denzer in Honey Creek Township. It is on the south flank of the syncline and the quartzite outcrops a short distance to the north. The outcrop was described in a recent paper[1] and only a brief summary is given here.

In the field the rock resembles rhyolite and has been described as such in previous reports.[2] Dark bands suggest flow lines, but on closer inspection appear to be true bedding, and even cross-bedded structures were noted on some of the weathered surfaces. The rock has two distinct facies: a massive, light greenish-gray, slate-like rock, and an extremely dense, black, hornfels-like rock with coarser bands of graywacke-like texture. The strike of the beds is nearly at right angles to the nearby quartzite and the dips approach verticality in contrast to the 10°–20° dips in the quartzite ridge.

MICROSCOPIC CHARACTER

Thin sections reveal clearly the fragmental character of the tuff. Sharply angular fragments of feldspar and rock particles are embedded in a fine crystalline groundmass that is distinctly different from the patchy, devitrified matrix of the aporhyolites. The denser facies show interlocking grains of feldspar and quartz with irregular

[1] J. T. Stark, "Pre-Cambrian Water-laid Tuff in the Baraboo District, Wisconsin," *Jour. Geol.*, Vol. XXVII (1930), pp. 466–71.

[2] Weidman, *op. cit.*, pp. 17–18; Alden, *op. cit.*, p. 61.

spots of sericite and chlorite, suggestive of typical textures of metamorphosed slates. The laminated portions show regular, parallel banding of fine and coarse material with gradational contacts and do not exhibit the sinuous curving of fluxion structures. The rock is thought to be a volcanic tuff, deposited in water and subjected to aqueous sorting. It is probably contemporaneous with the volcanic rhyolite.

OTTER CREEK GRANITE

LOCATION AND FIELD RELATIONS

The one known area of granite in the region occurs in Sumpter Township in the SE. $\frac{1}{4}$ of Sec. 32 and the SW. $\frac{1}{4}$ of Sec. 33, T. 10 N., R. 6 E., a short distance north of the old Myers mill. Ledges of the rock outcrop on both sides of Otter Creek where the upper part of the valley is cut deeply into the south slope of the quartzite ridge forming the south flank of the syncline. The valley walls rise more than 400 feet above the stream with granite forming the base and quartzite at the top with much coarse talus covering the slopes. In most places the talus covers the contact between the two formations although commonly they are within a few feet of each other.

The granite is dark, reddish gray to light pink, of medium to fine-grained texture, and is composed of red feldspar, quartz, and a considerable amount of dark green mineral. On each side of the valley there are more or less continuous outcrops extending over $\frac{1}{8}$ mile along the stream in bluffs of 50–100 feet. Commonly the lighter colored and usually finer grained rock forms the top of the ledges nearest to the quartzite. Dark green to nearly black dike-like areas, varying from 1 to 4 or 5 inches in width, show gradational contacts into the redder granite. In the field they suggest a differentiation or possibly a later intrusion. The granite nearest the quartzite shows evidence of shearing. An abundance of small quartz grains in the softer schistose matrix resembles an altered sediment.

MICROSCOPIC CHARACTER

The normal granite consists largely of feldspar and quartz with less than 5 per cent of biotite as the next most important constituent. The feldspar occurs in elongated, tabular crystals, polysynthetically twinned but, in general, so completely saussuritized, sericitized, and

kaolinized that extinction angles are not measurable. The interstices between the coarse feldspar grains are filled with quartz and less altered orthoclase feldspar, making a strikingly clear, angular pattern among the reticulated laths of highly altered plagioclase. Quartz is abundant in large grains, free for the most part of fracturing and strain. It forms nearly 50 per cent of the rock. The biotite, occurring in shreds and long plates, is more or less altered to chlorite.

FIG. 8.—Photomicrograph of granite from the Otter Creek area showing sericitized plagioclase with less altered orthoclase and quartz. With analyzer, ×50.

A small amount of iron oxide, largely hematite, stains the altered feldspars and is scattered in small grains through the rock. Epidote (pistacite) is associated with the chloritized mica, and a few pleochroic halos with zircon centers are present. Small apatite needles occur in all sections (Fig. 8).

The normal, reddish gray granite grades up into the lighter red variety. The latter is fine grained, the plagioclase is not so elongated nor as highly altered, and biotite is less abundant. Saussuritization gives way to sericitization and, in the more highly sheared portions, the feldspar becomes thick masses of sericite.

The dark green phase of the granite, which is gradational from both of the above types, differs from them chiefly in a greater degree of saussuritization of the feldspar, and in a larger amount of chlorite. Biotite has entirely disappeared, and the abundance of the chlorite accounts for the darker color of the rock. There is no evidence of a later, separate intrusion, and the green rock is considered a slightly more basic differentiation phase of the main mass.

FIG. 9.—Photomicrograph of granite from the Otter Creek area showing outlines of plagioclase completely obliterated by sericitization, with granulation and partial replacement of the quartz by sericite. With analyzer, ×50.

Nearer the quartzite contact the schistose granite is composed of many small, angular to sub-rounded quartz grains in a matrix of sericitic feldspar. The outlines of the feldspar crystals are completely obliterated, and a continuous sericitic mesh appears throughout the sections (Fig. 9). Groups of quartz particles, now separated by masses of sericite, show the same optical orientation and represent remnants of much larger grains. The suggestion of a sedimentary origin in the hand specimen is due to this extreme cataclastic structure which may be traced through all stages from the normal granite.

Small areas of the less altered granite in field outcrops appear intrusive into the highly granulated granite. Even under the hand lens the latter rock, with small particles of quartz in a mass of completely altered feldspar, bears a striking resemblance to a sheared and sericitized quartzite. It is only under the microscope that the gradation in granulation from one to the other is clearly established.

AGE OF THE GRANITE

Alden quotes authority for the granite's being intrusive into the quartzite and he mentions the occurrence of pegmatite dikes in quartzite of the Waterloo area, about 45 miles to the southeast and considered of the same age as the Baraboo quartzite, as evidence of late intrusions.[1] Weidman considered the granite as part of the pre-Baraboo quartzite basement.[2] No evidence was found by the writer that the Otter Creek granite cuts the quartzite. What in the field appeared to be altered quartzite in contact with the granite proved under the microscope to be highly altered granite with the cataclastic structures described above.

The evidence for post-Baraboo intrusion in the Waterloo area is unmistakable. The coarse-grained dikes, composed almost wholly of pink microcline, quartz, and light green mica, vary in grain from a fraction of an inch to 4 or 5 inches in diameter. The chilling effect of the intruded rock is shown in the finer grained edges of the dikes. The contact with the quartzite is sharp and there is but slight evidence of any exomorphic effects on the intruded rock. Alden thinks the intrusion was probably after the metamorphism of the original sandstone into quartzite. That the post-quartzite age of the Waterloo dike throws any light on the Otter Creek granite is questionable, because of the unsheared nature of the pegmatites as compared to the highly altered Otter Creek granite, the distance between the two outcrops, and the dissimilar lithologic character of the two intrusions.

No granite pebbles were found in the conglomeratic quartzite adjacent to the Otter Creek granite. The pebbles are of quartzite and chert, coarse and numerous but not dissimilar to the many

[1] *Op. cit.*, p. 61.

[2] *Op. cit.*, pp. 27–28.

horizons of intraformational conglomerate throughout the entire thickness of the Baraboo quartzite.

The absence of granite pebbles from conglomeratic quartzite in the cliffs above the Otter Creek granite, and the known occurrence of pegmatite in nearby areas may point to the Otter Creek granite as younger than the quartzite. On the other hand, the sheared zone between the granite and the quartzite, similar to zones at the Lower Narrows and Alloa, the lack of any intrusive evidence, and the position of the outcrop point to an age like that of the other igneous rocks in the Baraboo district.

DIORITE NEAR DENZER

LOCATION AND FIELD RELATIONS

Diorite outcrops in Honey Creek Township 1 mile northwest of Denzer in the NW. $\frac{1}{4}$ of SE. $\frac{1}{4}$ of Sec. 9, T. 10 N., R. 5 E. The rock forms a low mound of several acres less than $\frac{1}{8}$ mile south of the quartzite ridge which forms the south flank of the syncline, and is the westernmost exposure of igneous rock in the region. A mile and a quarter due north of Denzer, near the center of the N. $\frac{1}{2}$ of Sec. 10, T. 10 N., R. 5 E., numerous large blocks of diorite are distributed for several hundred feet along a small stream. Many of the blocks are 10–15 feet in diameter and some occur in the bed of the stream, apparently in place. Wells between these two outcrops encounter diorite at shallow depths; and it is assumed that the two localities represent summits of the same intrusive mass. The host rock is not exposed and the diorite on all sides is surrounded by the horizontal Cambrian sandstone.

The rock, in general, is a medium-grained, dark red plutonite with abundant pyribole, feldspar, and quartz. Variations in texture, both to finer and coarser grain, as well as in color, to nearly black, are common facies. Weidman speaks of "thin seams or ramifications of very fine-grained dark-colored, rhyolite-like rock which may be veins connected with the rhyolite formation."[1]

MICROSCOPIC CHARACTER

The microscope shows three-fourths of the diorite composed of feldspar, largely oligoclase with some andesine. Sericitization has to

[1] *Op. cit.*, p. 19.

some extent affected all of the feldspar, but it is much fresher than either the feldspar of the granite or the rhyolite. Hornblende, which probably was the next most abundant constituent, is now largely altered to granular masses of epidote in which the colorless variety predominates over the pistacite. Associated with the epidote is more or less chlorite. Red iron oxide stains most of the feldspar and is responsible for reddish phases of the rock in the hand specimens. Quartz is present in small grains, usually less than 5 per cent of the rock, although in many hand specimens it seems more abundant. Apatite is extremely common. Next to epidote, chlorite and carbonate are the most common alteration products.

AGE AND RELATIONS OF THE IGNEOUS ROCKS

Except the granite, which is possibly but not probably a later intrusive, all of the igneous outcrops, including the sheared conglomerate at the Lower Narrows, the breccia at Alloa, and the water-laid tuffs near Denzer, are believed to represent parts of the old crystalline floor upon which the Baraboo quartzite was deposited in the Middle Huronian seas. Thus they may represent a portion of the pre-Proterozoic complex or possibly belong to the Lower Huronian.

Actual contacts between the igneous rocks and the Baraboo quartzite have not been found. On top of the ridges at the Lower Narrows loose blocks of quartzitic conglomerate with coarse pebbles of rhyolite are apparently from the basal Baraboo formation, but these are not in place. Similar conglomerate with smaller pebbles is abundant in the talus slopes and quartzite bluffs of Otter Creek Valley. Much of the conglomerate ascribed by others to the basal Baraboo quartzite is believed to represent older rock. The reasons for this are: (1) the extremely sheared, schistose, and metamorphosed condition of the older rock as compared to the above-mentioned phases of the basal Baraboo quartzite; (2) the gradational contacts of the old conglomerate and breccia with the less highly sheared rhyolite; (3) the absence of contacts of any sort of the highly sheared rock with the quartzite; (4) the difference in dip and strike of the schistosity of the older sediments with the bedding of the quartzite; and (5) the occurrence of the igneous and associated rocks on the outer edges of the syncline.

It is natural to ask why more of the basal conglomerate of the Baraboo quartzite is not found. Except for loose blocks in various localities and possibly in the Otter Creek bluffs, conglomerate definitely recognizable as basal to the Baraboo formation is not known. Leith[1] has suggested that basal conglomerates are the exception and not the rule, "that over great flat surfaces of deposition conglomerates are either entirely absent or very small, thin, and inconspicuous; and that the large, conspicuous basal conglomerates usually mantle around some sharp elevations projecting above the general plane of deposition." That basal conglomerate of the Baraboo quartzite may have been thin or entirely wanting is a possibility. However, with so many exposures of the upturned quartzite syncline it would seem probable that some evidence of basal beds, whether true conglomerate or not, should exist.

In the base of the cliffs on the outer rims of the syncline, where the oldest quartzite might be expected to outcrop, the rock shows evidences of faulting and shearing. In no case has the shear produced rock comparable in any way to the highly altered conglomerate and breccia of the Lower Narrows and Alloa, yet there is indication in the shear planes of movement outward from the center of the fold.

It seems not improbable that this slipping of younger beds over older beds and formations may have resulted in the shearing of the younger non-conglomeratic (or non-basal) quartzite over thin and spottily distributed basal conglomerate. This would explain the nearness of distinctly non-conglomeratic quartzite to the igneous rocks of the old pre-Middle Huronian floor and account for the burial of some of the basal quartzite. In most of the gorges cut into the quartzite ridges, the base of the quartzite is covered with Cambrian sandstone. In the valley of Otter Creek the sandstone is missing and the pebbly quartzite here exposed may represent a basal phase.

[1] C. K. Leith, *Structural Geology* (1923), p. 281.

DRAINAGE CHANGES AND THEIR CAUSES IN THE ST. MAURICE VALLEY IN QUEBEC

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ABSTRACT

The present arrangement of the drainage of the St. Maurice Valley in the province of Quebec has little relation to the preglacial drainage. The modern St. Maurice River occupies parts of the valleys of several preglacial or interglacial streams and now flows up old valleys in two cases, and there are other examples of reversed stream courses. The pre-glacial drainage had a rectilinear pattern due to the geological structure, with the major streams flowing from northwest to southeast or from northeast to southwest. The upper parts of the St. Maurice, the Vermilion, and the Mattawin rivers have been turned from their former valleys by deposits of glacial drift and now flow northeasterly in parallel courses. Three lines of extensive glacial deposits indicate three halts of the ice sheet.

INTRODUCTION

The St. Maurice River drains a large area of wilderness north of the St. Lawrence Valley. The St. Maurice follows a very irregular course, and there is much evidence of an old, probably pre-Wisconsin[1] drainage pattern very different from the present one. This old drainage system will be described in so far as it can be reconstructed. It was certainly developed before the last ice advance; but, as to whether it was developed in an interglacial stage or in preglacial time, there is as yet little evidence.

The purpose of this paper is to present some of the preliminary results obtained from a series of geological visits to this little-studied region. The conclusions described herein have largely to do with drainage changes and with the evidences of halts or re-advances in the retreat of the ice sheet, but there are other important geological features which have not yet been sufficiently studied. The terraces along the St. Maurice are almost continuous from the St. Lawrence Valley to a point 20 miles above La Tuque, or a total north-south distance of about 100 miles; and it is hoped that from a detailed

[1] The age of the glaciation which caused the changes described in this paper has not been definitely determined for the region under discussion but has generally been considered as Wisconsin. The old drainage system here described is certainly pre-last-glacial and therefore that term is used in this paper.

study of the terraces and their associated features it will be possible to obtain information about postglacial tilting of the region.

Field work on the problem of pre-last-glacial drainage was begun in the fall of 1928 and continued in the summer of 1929. Additional field observations were made in the summer of 1930. Throughout much of this region travel is difficult, and good maps are non-existent. To overcome these difficulties, use was made of the aeroplane, and a flight was made over the entire region under consideration. This was very useful in correlating the scattered observations which had been made on the ground. Use was also made of air pictures which were fortunately available for parts of the area. These permitted detailed study of the topography, and from them it was possible to pick out key areas in which field work would be most valuable.

Since in a number of places it was desirable to learn the depth to bed rock and since borings were non-existent, recourse was had to electrical prospecting, by means of which the approximate depth to bed rock was determined.

Very little has been published on the geology of the St. Maurice Valley, and away from the railroad are large areas which have never been studied. The bedrock geology and mineral resources along the railroad were reported on by Bancroft in 1917,[1] and earlier geological work was reported on by Ells[2] in the southern part of the region under consideration. These works, however, leave almost untouched the many problems of glacial geology with which the present paper is concerned.

THE PRESENT DRAINAGE SYSTEM

The St. Maurice River has a drainage basin of some twenty thousand square miles, and it empties into the St. Lawrence at Three Rivers, midway between Montreal and the city of Quebec. Its headwaters are far to the north on the Laurentian peneplain. In the headwater region the relief is small, and a large dam on the upper part of the St. Maurice backs the water up to the St. Lawrence–

[1] J. Austen Bancroft, "Geology and Mineral Resources along the National Transcontinental Railway in the Province of Quebec," *Report on Mining Operations in the Province of Quebec during 1917*, pp. 128–68.

[2] R. W. Ells, "Report on the Geology of the Three Rivers Map Sheet," *Geol. Surv. Can. Ann. Rept.*, Vol. XI (1898), pp. 57J–58J.

Hudson Bay divide, forming a huge artificial lake at an elevation of 1,300 feet above sea level. The location of the St. Maurice River in relation to other rivers and to cities in eastern Canada is shown on the accompanying index map (Fig. 1).

Although the general course of the river is from northwest to southeast, there are many irregularities, and several of its important tributaries flow from southwest to northeast and turn sharply where they join the main river. Other abnormal features are the sharp angles in the main river at Flamand[1] and at the head of Rapide Blanc and also the retrograde course of several tributaries. The river does not have an even gradient but consists of a series of rapids separated by quiet stretches. These and other features indicate that the St. Maurice is not now flowing in its pre-last-glacial course but that it occupies parts of several old valleys.

GEOLOGIC STRUCTURE

The rock of this region is mostly gneiss, of both igneous and sedimentary origin, or granite. Narrow bands of the Grenville rocks, including bands of crystalline limestone, occur at various places. The dip and strike of the gneissic structure are extremely variable. The joint systems are more regular and have a rectilinear pattern. This pattern is shown much more clearly by the drainage lines, which are generally from northeast to southwest or from northwest to southeast.

Three significant valleys or canyons of probable structural origin are known. The first is a straight cut through the hills north of Rapide des Coeurs with its direction from N. 64° W. to S. 64° E. No through stream now occupies this valley, though at one time it may have been the course of the pre-last-glacial St. Maurice. A second structural valley was seen on the Rat River, which flows through a straight, deep, narrow gorge for several miles. Just before entering this gorge, whose direction is S. 69° E., the river turns sharply and turns again upon leaving it. The third case is on the west branch of the Bostonaise River on the west side of Bostonaise Island. Here the river divides, and the two distributaries follow different courses for about 10 miles, forming an island between them.

[1] The locations of all places mentioned are shown on Figure 2.

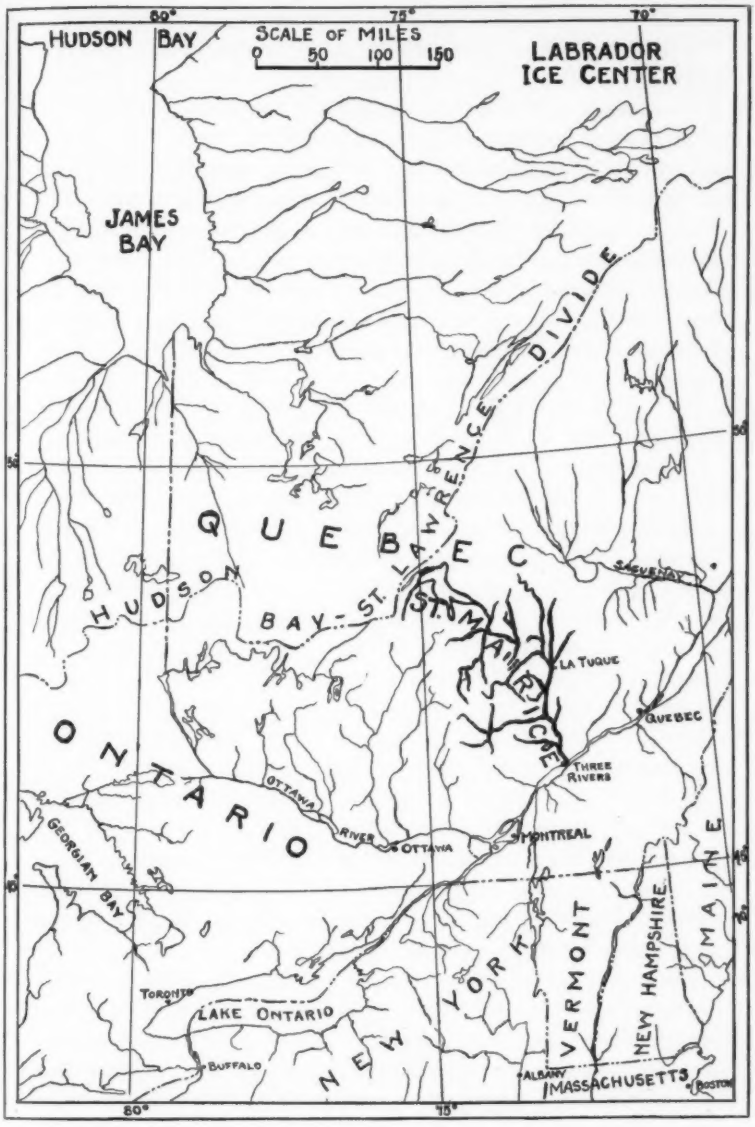

FIG. 1.—Index map showing location of the St. Maurice River

The eastern branch flows through a broad valley, but the western one flows S. 8° W. down a straight, narrow canyon cut in the peneplain.

The first and second cases are practically parallel and make an angle of approximately 75° with the third case. These directions are in general the ones followed by the major streams of the region. These remarkable straight gorges were probably controlled by faulting, and faulting rather than jointing is believed to be largely responsible for the rectilinear drainage pattern of the region. All three of these gorges were discovered and studied from the air, and would not have been known geologically for a long time except for the aeroplane.

ABNORMAL FEATURES OF THE PRESENT DRAINAGE

The St. Maurice River flows south from the great artificial lake at its headwaters to Manouan, at which point the Manouan River joins it from the south. Here the St. Maurice turns sharply to the east and plunges down a series of rapids. While at and above Manouan the valley is broad and floored with sand, and outcrops are scarce or lacking entirely, below Manouan the valley narrows, ledges are numerous, and the river falls over them, descending 140 feet in 11 miles. Since no difference is known in the rocks between the broad, upper valley and the lower stretch with rapids, the change in character of the valley indicates a different history of the two parts. This indication is further strengthened by the great breadth of the lower valley of the Manouan River. Like the upper St. Maurice Valley, the Manouan Valley just above Manouan Station is devoid of ledges, in contrast with the condition at Rapide Allard below Manouan, where ledges can be seen extending clear across the valley. All these facts point to the conclusion that these rapids are on an old divide and that formerly the St. Maurice continued southward through the lower part of the Manouan Valley.

Downstream from this series of rapids the valley opens out and is floored with sand down to Rapide des Coeurs, where the river plunges over ledges in a long rapid and through a narrow gorge. Here, also, the rocks do not differ from those a few miles upstream where the valley is very broad. In this case, also, this sudden change

in the width of the valley is due to the different history of the two parts, and the river is crossing another old divide at the rapids.

Below these rapids the river again enters a broad valley floored with sand and, turning a right angle at Flamand, flows northeast still in the broad valley. Beyond Flamand, however, the principal tributaries have retrograde courses; they flow from the northeast toward Flamand and turn an acute angle upon entering the main river. South of Flamand a broad valley extends into the hills, and, although it now contains no through stream, it is the natural southeasterly continuation of the St. Maurice and also of the tributaries which now have retrograde courses. About 16 miles northeast of Flamand the river makes another right-angle turn, and the valley narrows rapidly. In a few miles more the river plunges down Rapide Blanc, a long series of rapids, through a narrow, rocky valley.

At the head of Rapide Blanc the river is flowing over ledges, and rock is exposed on both sides of the valley. Nineteen miles upstream a boring failed to encounter rock at a depth of 105 feet, or 75 feet below the head of the rapids. These facts indicate that the St. Maurice is flowing up an old valley from Flamand to the head of the rapids, where it crosses an old divide and starts down a valley that was made by a small tributary of another river.

The foregoing facts show that the present St. Maurice River is made up of parts of several earlier river systems, and each of these will now be described in so far as it is possible to reconstruct them from the scanty data available. The present drainage system and the probable courses of pre-last-glacial streams are shown on the map of the St. Maurice Valley (Fig. 2).

FORMER DRAINAGE SYSTEMS

The St. Maurice flows in a broad valley for many miles above Manouan. If this course is projected southward, it leads up the Manouan River for a short distance and then up a long bay which extends to the southeast for 2 miles. A few miles up the Manouan River proper, beyond this bay, the valley narrows, the Manouan River falls over ledges, and it is evident that this is not the southward course of a large pre-last-glacial river. Southward from the bay, however, a valley leads into a group of hills which appear from the

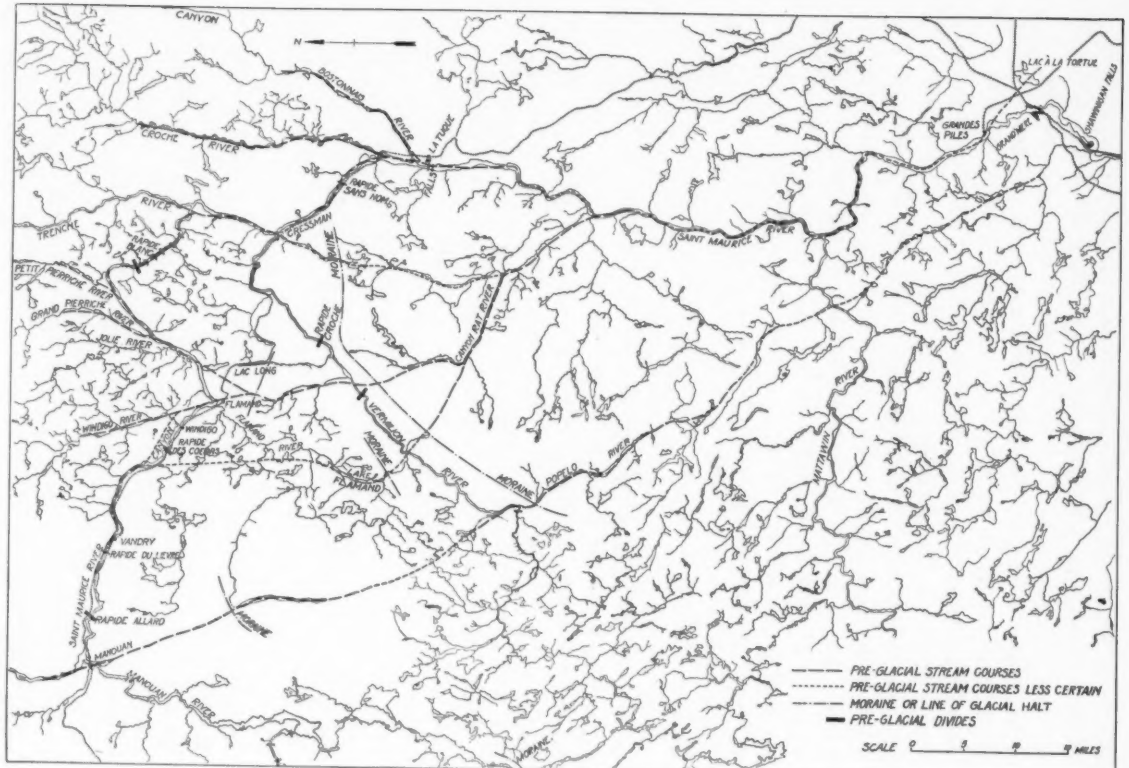

FIG. 2.—Map of the St. Maurice Valley, showing courses of pre-glacial streams, pre-glacial divides, and moraines

air to be a moraine; and south from these hills a valley leads to a very long, narrow lake extending 10 miles toward the south. Another broad, straight valley leads from this to a maze of lakes in flat land on the upper part of the Vermilion River at an elevation of about 1,300 feet above sea level.

The region surrounding these lakes is essentially a reconstructed peneplain and shows the condition of the upland before it was uplifted and dissected, since, except for the drainage pattern, the surface today in its general appearance restores this portion of the Laurentian peneplain as it stood before the present valleys were eroded. This restoration has been accomplished by filling the valleys with glacial deposits, with the result that the streams now meander over plains of sand, there is little relief, and few hills rise much above the general level. In this headwater portion of the Vermilion Valley the present streams have scarcely begun to remove the glacial deposits from the earlier valleys; whereas farther downstream considerable progress in this direction has been made. We thus have at this place the reconstruction of the peneplain preserved.

Across this plain the course of the pre-last-glacial St. Maurice is obscure, but to the southeast a striking valley now occupied by the Popelo River leads from the Vermilion River toward the Mattawin River, and it is probable that this marks the course of the old river. From the air, moraines were seen in the lower part of the Popelo Valley. The stream now flows northerly through these moraines to the Vermilion River. It is possible that another moraine blocks the valley near the head of the Popelo, but that region has not been visited. The Popelo Valley has not been followed, but the probable course of the earlier drainage, as deduced from the arrangement of lakes and streams, is shown on the accompanying map.

The course of the pre-last-glacial river appears to rejoin the present St. Maurice near Shawinigan Falls, but the southern part of its course is not definitely known. At Shawinigan Falls the St. Maurice is now flowing over ledges and is not in a preglacial valley. This old river, which extended from above Manouan to the vicinity of Shawinigan Falls, may well be called the "pre-last-glacial St. Maurice," as the upper and lower parts of its course were the same as the present St. Maurice.

FIG. 2.—Map of the St. Maurice Valley, showing courses of pre-glacial streams, pre-glacial divides, and moraines

Rapide Allard east of Manouan then marks an old divide between the earlier St. Maurice drainage and that flowing eastward down the present St. Maurice Valley as far as Rapide des Coeurs. That the old drainage did not go down these rapids is indicated by the fact that the depth to bed rock, as determined in a number of places by electrical prospecting about 15 miles upstream from the rapids, was found to be at least 20 feet lower than the bedrock crest of the rapids. If the bedrock floor is projected downstream on a reasonable gradient, it will be well below the crest of the rapids. It is possible that the old stream went north of the rapids through the structural valley previously referred to, but it is equally probable that it went through a low place in the hills into the Flamand Valley. Further investigation is needed for this region between Rapide des Coeurs and the Flamand. From this latter valley, however, there is evidence of a buried valley across to the Vermilion and southeast from that stream into the headwaters of the Rat River.

The drainage east of Rapide des Coeurs will next receive consideration. The Windigo River comes down from the north and turns to the west a few miles before joining the St. Maurice; but a valley continues southward, joining the St. Maurice at Flamand, and this is probably the old course. As has already been shown, the direction of the tributaries indicates that the part of the St. Maurice between Flamand and Rapide Blanc is now flowing in the reverse of its former direction. It appears, therefore, that formerly a stream flowed from the northeast up the present valley of the St. Maurice to Flamand and there joined the pre-last-glacial Windigo. From Flamand a broad valley leads south into the hills toward the Vermilion River; and, although it does not now extend through to the Vermilion, it is very probable that there was an old valley in this vicinity which is now blocked by morainal deposits. Extensive sand deposits along this line give evidence that the pre-last-glacial topography is deeply buried. South of the Vermilion there are two gaps in the hills where a low dam on the Vermilion would turn that river over a broad, sandy divide into the valley of the Rat River. One of these gaps is believed to mark the course of the old valley. From this point a broad valley floored with sand leads southward to the end of the structural gorge previously described. Here the pre-last-glacial

stream was joined by the one which came from above Rapide des Coeurs across the Flamand and Vermilion valleys into the Rat Valley. The drainage of the joint stream probably went through this gorge, though there is some evidence of an old valley parallel to it and a few miles to the south. The Rat River joins the St. Maurice some 20 miles below the head of the gorge. This drainage system may well be referred to as the "pre-last-glacial Windigo-Rat system."

The divide at the head of Rapide Blanc separated the drainage just described from a stream which flowed southward down the valley now occupied by Rapide Blanc to the mouth of the Trenche River. At this place electrical prospecting has shown that the depth to bed rock is over 100 feet. The pre-last-glacial Trenche continued southward in the valley now occupied by the St. Maurice to Cressman, and below that place its course is uncertain. Leading southward from Cressman is a striking valley, and there is some evidence that the Trenche formerly flowed down this and joined the Rat at the mouth of the gorge. This route has been followed in the air, there is an open valley all the way through, and the present divide appears to be formed by a moraine.

The valley now occupied by the St. Maurice continues southeasterly from Cressman and is joined by the Croche Valley a few miles north of La Tuque. In this section of the St. Maurice there are rock benches, remnants of an old valley floor 50 feet or more above the river. These are mentioned by Bancroft[1] and are interpreted by him as indicating that the river is now actively intrenching itself in an earlier valley floor. Determinations of the depth to rock under the river by electrical prospecting methods have shown that bed rock is more than 100 feet below the present river level. This deep, narrow gorge in the old valley floor and the uplift which caused its erosion preceded the last stage of glaciation. The river is now merely clearing the débris from its old gorge.

The Croche River flows through a remarkably broad, straight, steep-walled valley different in character from that occupied by the St. Maurice below Cressman, though the latter is now much the larger stream and the rocks are generally the same. To learn more about these valleys and find out which was the major valley in earlier

[1] J. Austen Bancroft, *op. cit.*, p. 137.

times, determination of the depth to bed rock by electrical prospecting was carried out in each valley and also in the joint valley below La Tuque. This was done by the Schlumberger Electrical Prospecting Methods purely as a scientific problem, and the author's thanks are due this company for its valuable assistance.

The town of La Tuque is located on a sand terrace in the broad valley of the St. Maurice River 550 feet above sea level. The river flows at an elevation of a little less than 500 feet to the falls, where it descends to less than 400 feet. At the close of the glacial period the valley was filled to the 550-foot level, and the river meandered over a sand plain and happened to flow above a low saddle in a buried rock ridge at the west side of the valley. The river cut down and has become superimposed upon the rock, which retarded erosion; while below the ridge the sand was easily removed and the falls were produced. Below the falls the river cleared its valley to a width of half a mile, and old meander scars can now be seen in the high bluff below the town. By electrical prospecting methods it was found that the elevation of bed rock in the middle of the valley just below the town is practically at sea level, giving a depth of over 500 feet of glacial deposits in the valley.

The place tested in the Croche Valley is 8 miles north of La Tuque. The width of the valley at this point is about 4,000 feet, and bed rock was found about 300 feet below the surface at an elevation of 217 feet, but it is doubtful if this was in the deepest part of the valley. This gives a gradient from this point to La Tuque of not over 25 feet per mile for the bedrock floor of the buried valley. Similar tests were carried out in the St. Maurice Valley 10 miles above La Tuque, at which point its width is about 1,400 feet. The elevation of the bedrock floor was found to be approximately 400 feet, while the present river is at an elevation of 520 feet, giving a gradient of 47 feet per mile for the pre-last-glacial valley to its junction with the Croche Valley. Comparison of these two valleys makes it seem probable that in earlier times the major stream was in the Croche Valley with a tributary from a divide southeast of Cressman flowing down a steeper grade in the valley now occupied by the St. Maurice. If this was the case, the pre-last-glacial Trenche River continued south from Cressman, while in the other case it turned and was tributary to

the Croche. The pre-last-glacial Croche joined the Bostonaise near La Tuque, and the joint stream was the architect of the deep valley below La Tuque. As far as is known now, this stream followed the present course of the St. Maurice to Grandes Piles where the present river leaves the Laurentian Highlands. The pre-last-glacial Windigo-Rat system was then tributary to the Croche-Bostonaise system.

Below Grandes Piles the St. Maurice does not follow a preglacial course, as is indicated by the falls over ledge at Grand'mere, Shawinigan Falls, La Gabelle, and Des Forges. The southern extension of the stream which occupied the St. Maurice Valley from La Tuque to Grandes Piles was probably to the southeast from Grandes Piles. Since the rock floor of this buried valley is at sea level at La Tuque, it is probably far below sea level south of Grandes Piles; and evidence to this effect is given by borings at Three Rivers and Quebec. At the first-named place no rock was found at an elevation of minus 84, and at the latter place rock was encountered at 229 feet below sea level. These borings were not necessarily in the deepest parts of the buried valleys, and the bottoms of these valleys are probably still deeper. These facts prove that the land stood much higher in relation to the sea when these valleys were eroded before the last stage of glaciation.

The lower part of the Mattawin Valley was drained by the pre-last-glacial St. Maurice, and the upper part of the Mattawin was probably drained by one or more streams, but that region has not been studied as yet. The St. Maurice Valley was thus drained preceding the last ice advance by four or more rivers each flowing from northwest to southeast. These streams have been turned aside in three places, with the result that there are three west-to-east rivers: the upper St. Maurice, the Vermilion, and the Mattawin, all of which join and form the lower St. Maurice.

EXPLANATION OF THE DISARRANGEMENT

The cause of the disarrangement of the older drainage appears to be the blocking of the streams by glacial deposits along three lines. The northern line is between the upper St. Maurice and the Vermilion rivers, the middle line is south of the Vermilion, and the southern line is south of the Mattawin River.

On the northern line moraines are known definitely at the southern headwaters of the Manouan drainage, and they have been seen from the air across the old valley of the St. Maurice south of Manouan Station, and also south of Lake Flamand. Farther east between the upper St. Maurice and the Vermilion are extensive outwash plains. These facts indicate a re-advance or halt of the ice front along this line. South of the Vermilion, extensive outwash plains of sand and three probable moraines are known. These are in a line almost parallel to the river, and it is likely that there was another halt of the ice sheet here. The same conditions probably exist south of the Mattawin, but there has been no opportunity to investigate that region. The arrangement of the postglacial drainage and the character of the glacial deposits thus indicate three halts along approximately parallel east-west fronts in the retreat of the ice sheet.

Between the Vermilion and the upper St. Maurice, and also south of the Vermilion, are extensive outwash plains and valley trains. These two sets of outwash plains were not formed during a steady, unbroken retreat of the ice, for had that been the case, there would have been a continuous plain sloping to the south, and north-south rivers would have been formed. Instead of that, we find a series of outwash plains sloping down into the Vermilion Valley and then another series beginning a little higher and sloping southward.

The peculiar arrangement of the present drainage is due both to the blocking of valleys by glacial deposits along definite lines and to the rectilinear arrangement of those valleys due to structural control. There are two southwest-northeast lines of drainage which are parallel and which are especially significant. The first is formed by the Flamand River from its headwaters to the St. Maurice at Flamand and by the St. Maurice down to the mouth of the Little Pierriche, and the second is the Vermilion River below the Popelo River. It has been shown that neither of these lines was followed by any one pre-last-glacial stream but that three streams flowed across these lines. These two lines are believed to represent zones of structural weakness, and the preglacial streams which crossed them developed tributary valleys in these zones which were approximately at right angles to the master-streams. There was thus a trellis drainage pattern with a series of tributary valleys along each of these structural

zones, and probably along other lines which have not yet been definitely recognized.

When the streams attempted to take new courses to the sea after the retreat of the last ice sheet, they were blocked along three lines. The damming of the main north-south valleys by glacial deposits caused lakes which extended up the branch valleys and over the divides. Thus, long, narrow lakes were formed which overflowed at their northeast ends where the moraines were lowest. These lakes were filled with sediments; and thus the flat-floored valleys of the St. Maurice below Flamand and of the Vermilion, which contrast so strongly with the narrow gorges, were formed; and, since the lakes had their outlets at their northeast ends, northeastward-flowing streams were produced.

CONCLUSIONS

The present drainage system of the St. Maurice Valley is very different from that which preceded the last ice invasion. Although the general course of the streams is from north to south, there are sections of the St. Maurice and many tributaries which flow northeasterly. Before the last glacial stage four or more southward-flowing streams drained the area of the St. Maurice Valley. The lower parts of the valleys of these streams are now below sea level, indicating that the land stood much higher in relation to the sea when these valleys were formed.

The pre-last-glacial valleys of this region were blocked by heavy deposits of glacial drift along three lines which trend from southwest to northeast. The streams were turned to the northeast by these barriers, and the present drainage system resulted. The arrangement of the postglacial drainage and the character of the glacial deposits indicate three or more halts or re-advances of the ice along approximately parallel east-west fronts in the retreat of the ice sheet.

PETROLOGY OF THE IGNEOUS ROCKS FROM THE WEST GIR FOREST, KATHIAWAR, INDIA

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INTRODUCTION

This paper[1] embodies the results of investigation on a collection of igneous rocks from the western part of Gir Forest and its neighborhood made by Dr. J. W. Evans during 1893 and 1894. To him thanks are due, not only for lending the specimens, together with the relevant field notes, but also for initiating the writer into the geology of the area. Despite its highly interesting character, this region has not received the attention it deserves from geologists. Perhaps the most noteworthy literature extant on the subject is a brief memoir on Kathiawar by Fedden;[2] but this, purposing, as it does, to embrace within its scope the whole province of Kathiawar, with its diverse formations, fails to do full justice to the area under consideration. Mention should also be made of a paper on the magmatic differentiation on Mount Girnar[3] and of another on the petrography of rocks from the Girnar and Osham hills.[4]

The province of Kathiawar forms a peninsula between the gulfs of Cutch and Cambay on the western coast of India. It has an irregular shape with undulating surface and low, ill-defined ranges of hills. The central portion of the country is the most elevated, and not far south of this are several prominent ridges and detached hills of volcanic origin. Of these, the Junagarh group, with its lofty peak Girnar, is the most conspicuous; and to the southeast of this group begins the Gir range stretching away for 20 or 30 miles in an easterly direction.

[1] This formed part of the work carried out at the Imperial College of Science in 1924 while the author was a research student before entering the Survey.

[2] F. Fedden, *Mem. Geol. Surv. Ind.*, Vol. XXI, Part II (1885), pp. 1–64.

[3] K. K. Mathur, V. S. Dubey, and N. L. Sharma, "The Magmatic Differentiation on Mount Girnar," *Jour. Geol.*, Vol. XXXIV (1926), p. 289.

[4] M. S. Krishnan, *Rec. Geol. Surv. Ind.*, Vol. LVIII, Part 4 (1926).

The rocks representing extrusions or minor intrusions are, with only a few exceptions, basic, and are associated in age with the plateau basalts of the Deccan Trap, but differ from them in certain salient features characteristic of the whole of Kathiawar. Unlike the Deccan traps, there is here distinct evidence of the usual cone type of volcanic activity, e.g., in Girnar; further, the basic flows are found associated with acid ones, particularly toward the top. But the most interesting feature of this area is a series of basic dikes run-

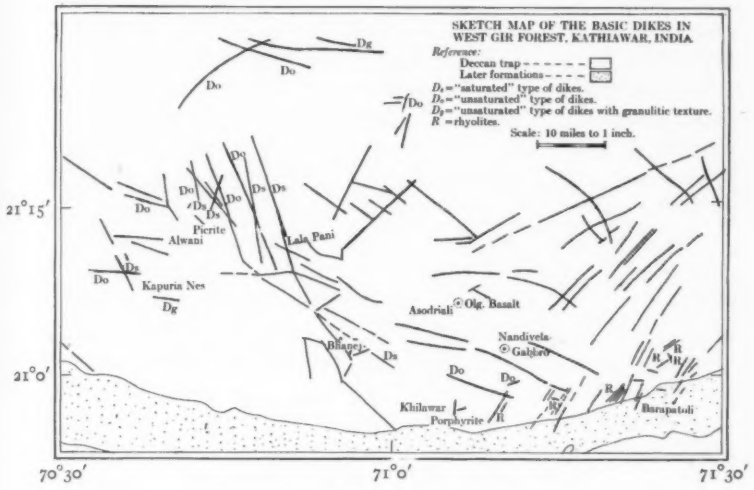


FIG. 1

ning more or less parallel to one another at small distances apart and frequently intersected by others nearly at right angles; some of the dikes are traceable for long distances. From the appended sketch map (Fig. 1), which gives a broad general idea of their disposition, it will be noticed that, barring the northwest part, the general trend is about west-northwest–east-southeast to northwest-southeast, while the cross dikes are approximately in a northeast-southwest direction. The walls of these dikes are, as a rule, vertical, with "clean, well-marked faces"; but sill-like intrusions are not uncommon, and in a few cases they may bifurcate. Occasionally passage into vesicular or amygdaloidal structure toward the top can be seen.

In passing, it may be recorded that it is in the southeast of the area under consideration that acid rocks (chiefly rhyolites) are best developed. Here all the dikes, both acid and basic, have a more or less northeast-southwest trend, and even the coast line is approximately parallel to the pronounced direction of the dikes.

DESCRIPTION OF ROCKS

BASIC TYPES

Megascopic features.—In hand specimens the rocks are grayish green to black with brownish tints, the least olivine-rich being usually the most black. White streaks of feldspar phenocrysts, when present, or amygdaloidal patches may break the somber monotony. On extensive decomposition they lose their depth of color and turn to purple-red. In granularity they vary from dense aphanitic through fine-grained (of most common occurrence) to comparatively coarse-grained types.

Textural features.—The variation in these rocks as regards texture is sometimes striking. While ophitic texture is the rule and may be observed both in fine- and coarse-grained types (*vide* microphotograph), there are gradations from this to intersertal or intergranular types due to internal movements within the magma during consolidation. The groundmass is very fine-grained, and in some cases suggests andesites, although the plagioclase in the groundmass defies determination owing to its extremely diminutive size. Glomeroporphyritic aggregates of feldspar, frequently cracked and occasionally enclosing other substances, are not at all uncommon. Porphyritic texture is exceedingly frequent among the olivine-bearing dolerites. In types very rich in augite, a tendency was observed for this mineral or its derivatives to assume a radiating structure; in the basalts in which this constituent usually occurs in abundance it is found in close association with feldspars, giving rise to cruciform or radiating clusters similar to those observed by Holmes[1] in Arctic basalts. Occasionally kelyphitic structure between olivine and plagioclase can also be observed in some of the specimens, and hypidiomorphic aggregates of augite and magnetite in others. But the most

[1] A. Holmes, "The Basaltic Rocks of the Arctic Region," *Min. Mag.*, Vol. XVIII (1918), pp. 180–223.

interesting character is presented by vesicles, small or large, occurring not infrequently and filled with a variety of minerals including several zeolites, testifying to the effect of paulopost vulcanicity. In these rocks, which are mostly doleritic, glass is not common, and, if present, either is charged with dust or skeletal crystals of magnetite or is yellowish and palagonitized.

Xenocrysts are rare, and the only instance of their occurrence is in the form of a few rounded grains of quartz (*vide* microphotograph) bounded by a shell of augite granules embedded in glass, the whole presenting roughly a rectangular outline.

It is difficult to determine the order of crystallization in the amygdules. Chlorite usually precedes all, but may have succeeded lime zeolites, while silica in all its forms is the last to be deposited. A remarkable case of partial replacement of heulandite by quartz, where the alteration commenced at the walls and proceeded inward, may be compared to a similar phenomenon, described by Holmes, in the Tertiary volcanic rocks of the district of Mozambique.[1]

The proportion of the constituent minerals may vary considerably in rocks grouped under the same name. Thus, in a few dolerites olivine is present in small quantity or is absent; in others it is so abundant as to warrant the rock being designated a picrite. The nature and proportion of iron ores also may vary a good deal in otherwise similar rock species, but in the bulk of the specimen feldspar takes the premier place by volume. Generally speaking plagioclase, augite, and olivine make up approximately 95 per cent of the volume; neither hornblende nor biotite has been recorded as primary minerals in any of these rocks.

MICROSCOPIC FEATURES

1. *Basalts.*—There are not many specimens compared with dolerites, which form the bulk of the present collection. A good many specimens are decomposed and are of a greenish-yellow color. Usually holocrystalline, they occasionally carry dark glass abounding in magnetite in the form of dust, grains, or skeletal crystals. Olivine, whether altered or otherwise, is comparatively rare except as phenocrysts. When abundant, feldspar microlites form a sort of felted ma-

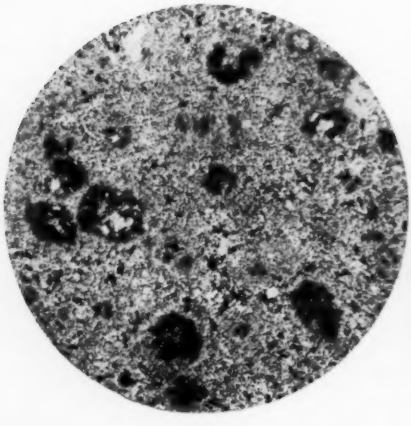
[1] A. Holmes, *Quar. Jour. Geol. Soc.* (1916), p. 252.

198 T

197 V

201 Z

200 A



290 M

205 A

FIG. 2.—For explanation see opposite page

trix. Vesicles are common and contain silica in all its forms, and chlorite—the latter, on low-grade metamorphism, altering into needles of actinolite. Prehnite, heulandite, and pyrite are also of frequent occurrence. Feldspar phenocrysts are often considerably altered, and in one case have given rise to zeolites; golden yellow spherules of palagonite were noticed from specimens from the hill near Barpatoli. Specimens from Asodriali Nes on the west of River Raval might be termed oligoclase-basalts from the presence of microlites of this variety of feldspar in the groundmass.

2. *Pyroxene-andesite.*—In thin section this shows phenocrysts of radiating andesine feldspar against a dark background. The groundmass is pale brownish, exceedingly fine-grained, more or less hyalopilitic, and with numerous microlites of feldspar and granular magnetite and augite. It is highly vesicular, the vesicles being filled with calcite and others of the usual suite of minerals except zeolites. Only a few specimens of this rock are definitely known; and since even the one in the present collection was not found *in situ*, it cannot be decided whether it occurred in the form of a lava flow or as a dike—probably the former.

3. *Dolerites.*—Leaving aside the two sporadic types, viz., the one from the north of Haliad Mota illustrative of granulitic texture, and the other from the south of Kapuria Nes showing a fine-grained, intergranular to micrographic groundmass of feldspar and augite, the vast majority of specimens are typical olivine-dolerites. No porphyritic texture is developed in some of the specimens (e.g., Gil Range, west of Piawa), and their coarse-grained texture warrant their being designated "ophitic gabbro." Again, another from the range to the north of Alwani has been termed a "picrite" owing to the prepon-

EXPLANATION OF FIGURE 2

198 T.—Dolerite with xenocryst of quartz. From hill near Sadaon Sap Nes. C.N. ×23.

201 Z.—Olivine-dolerite with aggregates of feldspars. From valley near Ambliala. O.L. ×25.

290 M.—Sperulitic granophyre. From Godhan. O.L. ×25.

197 V.—Dolerite with abundant iron ores (titaniferous) in the groundmass. From Lilapari. O.L. ×25.

200 A.—Oligoclase-basalt. From west of River Raval. O.L. ×15.

205 A.—Part of amygdale with sheaves of prehnite in dolerite. From Sadaori. C.N. ×12.

derance of olivine with only a few laths of feldspar enclosed in poikilitic patches of augite, the crystals of which are in some cases large and twinned.

Among the remaining specimens, two broad types may be distinguished. On the basis of chemical analyses, one may be termed "saturated," since it possesses a small amount of normative quartz, although among the mineral constituents there may exist a little olivine. This type is rich in TiO_2 and less markedly porphyritic, with the feldspars tending to cluster; the pyroxenes are generally enstatite-augite except in a few cases such as those from the hill east of Sandbera and the range south of Piawa, in which serpentinous pseudomorphs of orthorhombic pyroxene intergrown in the center of monoclinic varieties can be identified. Ragged flakes of hematite are also to be found. Ilmenite as well as titaniferous magnetite is among the last minerals to finish crystallizing. In short, the characteristics of this type closely accord with those of the doleritic and basaltic flows of the Deccan Trap.

The second type is more widely distributed. It is generally markedly porphyritic, with abundant olivines, sometimes forming large crystals. It differs from the Deccan traps in that traces of Cr_2O_3 were observed in it.[1] The pyroxenes are of pale color, brownish or even purplish, pleochroic, and occasionally exhibit pronounced hourglass structure; the primary iron ores are magnetite and ilmenite. As already stated, porphyritic and intergranular texture are sometimes pronounced; and, particularly in the coarse-grained rocks, a later anhedral accretion of clear, untwinned plagioclase may, to a certain extent, detract from the ophitic character.

An almost universal feature in all the types of dolerites consists of patches of chlorite of vermicular habit; in these, calcite occurs usually in granular form, except in an individual specimen from the ridge on the west of Ambarajthali, in which a fairly large flake was noticed. A rather remarkable example of metamorphism is found in a solitary example of meta-dolerite from Godhan Hills (an area abounding in

[1] This inference was drawn from the analyses of Deccan traps by Washington. But Dr. Fermor points out that there are laterites derived from Deccan traps with Cr_2O_3; and as such, this view is untenable. Still the presence of this constituent by itself is not sufficient to prove the identity of these dolerites with the traps.

quartz-porphyries), in which all the augite crystals have been converted into uralite.

4. *Gabbros.*—Very little is known about the geological occurrence of the specimens of the gabbros save that they are found at a pretty high altitude near the southern end of Nandivela. The textural features have already been enumerated. There is no olivine. The plagioclase[1] crystals are zoned and range in composition roughly from An. 70 per cent to An. 60 per cent. The pyroxene is slightly purplish to brown, and is extensively converted to a yellowish-green amphibole (actinolite) toward the edges, in the outermost rims of which, when adjacent to feldspars, a green, strongly pleochroic hue may be observed. In places, alteration has resulted in chlorite, clots of magnetite, and even iron hydrates. Among other primary minerals, magnetite and biotite in one of the specimens are noteworthy. The mesostasis of micropegmatite, consisting of quartz and orthoclase, has also been described.

CHEMICAL FEATURES

Table I gives the results of chemical analyses of some of the typical specimens. It will be noticed that the "saturated" type is remarkable for its high FeO and TiO_2 content, a feature in common with the "plateau basalt," and in it the FeO/MgO index is higher than unity; whereas the "unsaturated" types contain a high percentage of MgO, and low TiO_2 and alkali content, suggesting that they belong to a later stage. At the same time, these latter types contain no inappreciable amount of iron, leading to the conclusion that the olivines may be tolerably ferriferous. This view, considered in the light of Vogt's generalization,[2] tends to prove that, during the process of crystallization of ferromagnesian silicates in an igneous magma, there is no selective process at work between FeO and MgO. The sympathetic variation of Fe_2O_3 and Na_2O is also to be noted.

An example of solitary occurrence of a rock type from near Khilawar on the Dhokarwa-Khilawar Road, which cannot be grouped under any of the foregoing headings, may be mentioned here. It is altered, vesicular, greenish-gray, and fine-grained. In thin section

[1] Wherever possible, the species of plagioclase feldspar in all these rocks was confirmed by the employment of Federov's universal stage microscope.

[2] J. H. L. Vogt, *Jour. Geol.*, Vol. XXIX, pp. 537–38.

it presents a considerably decomposed matrix with unidentifiable feldspar, a little quartz of partly or entirely secondary origin, and abundant streaks of partially bleached biotite yielding in places rutile needles. Numerous phenocrysts of brown hornblende with re-

TABLE I

(Analyzed by S. K. Chatterjee)

	Number*						
	Saturated	Unsaturated			200A	200Q	201X
	195T	201T	200B	206C			
SiO_2	48·18	50·47	46·90	48·53	47·50	51·39	48·14
Al_2O_3	13·51	13·10	14·29	13·81	17·12	15·06	15·86
Fe_2O_3	3·26	0·43	1·82	1·90	2·77	3·24	6·01
FeO	8·29	10·06	8·31	7·69	7·68	7·97	5·07
MnO	0·46	0·35	0·27	0·90	0·15	0·27	.....
MgO	7·01	11·06	8·95	11·20	4·00	6·66	5·76
CaO	10·67	10·94	13·29	10·46	8·37	8·49	9·27
Na_2O	2·65	0·97	1·59	1·83	5·75	2·17	2·97
K_2O	0·50	1·24	0·56	0·59	0·64	1·14	1·66
H_2O+	1·14	0·24	2·89	2·91	1·96	1·51	1·43
H_2O-	0·37	0·06	.....	0·39	1·04	.....	0·34
TiO_2	2·98	0·98	0·82	0·06	1·37	0·62	3·76
NiO	tr.	0·08	tr.	n.d.	.....	.....	.....
Cr_2O_3	.....	0·08	.....	.....	.....	.....	.....
P_2O_5	0·60	tr.	0·40	nil	tr.	0·20	.....
Cl	0·03	.....	tr.	.....	.....	0·03	.....
CO_2	nil	nil	0·10	nil	1·50	1·32	.....
Total	99·65	100·02	100·19	100·27	99·85	100·07	100·27

* These numbers are those of specimens in the collection of Dr. J. W. Evans.

No. 195T. = Dolerite, from near Khambha.

No. 201T. = Coarse olivine-dolerite, from hill near Sonaria and of road east-southeast of Salwa.

No. 200B. = Olivine-dolerite, east of Asodriali Nes, near River Raval.

No. 206C. = Olivine-dolerite, south of Kapuria Nes.

No. 200A. = Oligoclase-basalt, west of River Raval (2 miles east of Asodriali Nes).

No. 200Q. = Gabbro, from southern end of spur of Nandivela.

No. 201X. = Pyroxene-andesite (?) decomposed, little west of Ambliala.

sorbed margins, large phenocrysts of altered feldspar with inclusions of iron ores, and a few patches of carbonates with borders of iron oxide, possibly representing altered olivine, may also be seen. Vesicles filled with secondary quartz and chalcedony, and big patches of quartz perhaps of quasi-foreign origin, are also of frequent occurrence. The rock, probably a basic hornblende-porphyrite, displays many of the characters of a lamprophyre and could

have been so named but that, among other reasons, the feldspar occurs in two generations.

ACID TYPES

Associated with the basic types cited above are some acid rocks in the form of irregular intrusions; but they are typically developed on the east of the area under consideration and show a general northeast-southwest trend. These rocks may be classified under the following three groups:

1. In the northwest is found spherulitic granophyre with corroded phenocrysts of water-clear quartz, and with altered orthoclase and oligoclase feldspars presenting roughly square or rectangular shape. The bulk of the chlorite is secondary after augite. In some of the specimens oligoclase surrounded by a border of kaolinized orthoclase may be seen. Among the other constituents present may be mentioned shreds of bleached biotite and grains of apatite and zircon.

2. The next group is more important. It may be called the Bhanej type after the place of its occurrence (Bhanej Nes). The rocks of this type have a cherty appearance, are occasionally mottled, and are cream, greenish, purplish, or lavender-gray colored; they are frequently intermingled with brown patches of iron oxides. They are extremely siliceous, with silica content ranging between 82 per cent and 88 per cent, and in thin section invariably present a mosaic of fine-grained quartz. Signs of secondary silicification may be observed. A few laths of feldspar, secondary mica, and grains of zircon, are also present in some.

3. On the eastern part may be seen dikes of pitchstone and rhyolite, both of which are typically developed in the Osham Hills,[1] lying far away in the north of this area. Rhyolites are far more common than the pitchstones and are subjected to secondary silicification. Unlike the Pavagadh rhyolites with plagioclase as basic as andesine, and augite, these contain phenocrysts of quartz and sanidine.

Finally, the author feels grateful to the director of the Indian Geological Survey for kindly granting the necessary permission to publish this paper; and to Dr. T. V. M. Rao, of the Imperial College of Science, South Kensington, for editing the same.

[1] Krishmar, *op. cit.*

TENSIONAL SURFACE FEATURES OF CERTAIN BASALTIC ELLIPSOIDS

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ABSTRACT

The subaqueous distention of the surface of ellipsoidal masses of basalt is shown to have resulted in crustal displacement and, therefore, in the formation of remarkably regular angular corrugations. Banded joint cracks are explained by their periodic advance owing to the surface contraction of the pillow during rapid solidification.

On the Columbia River Plateau in central Washington, the aqueous chilling of basaltic flows has achieved various effects dependent on both the fluidity of the advancing lava and the depth of the water.[1] Highly fluid lava advancing into shallow water has been shown to build well-defined foreset-bedded breccias consisting largely of granulated sideromelane, the transparent variety of basaltic glass. "The inclined bedding is preserved both by the thin sheets and the ropy or ellipsoidal masses which failed to granulate."[2] Over this heterogeneous basal phase a flow would have advanced almost as if on dry land.

Some of the ellipsoidal masses embedded in the breccias are detached, but many may be found to be basal protrusions from the inclined sheets which characteristically taper upward. Locally, the pillows show an unusually high degree of symmetry probably owing, in part, to the support offered by the enclosing granulated glass. The undulating surface of these masses is usually divided into polygons by a network of deep cracks, which average about 2 inches in depth. The angular units thus formed are in turn subdivided by innumerable systems of smaller cracks. The surface has been spalled from many of these smaller divisions, which average 1–2 cm. in diameter. Some of the cracks, especially the deeper ones, exhibit rounded margins, indicating that they were formed prior to the com-

[1] Richard E. Fuller, "The Aqueous Chilling of Basaltic Lava on the Columbia River Plateau," *Amer. Jour. Sci.*, Vol. XXI (1931), pp. 281–300.

[2] *Op. cit.*, p. 284.

plete solidification of the glassy selvage. All of these features have been more or less modified by subsequent palagonitization.[1]

ANGULAR CORRUGATIONS

Locally, the major segments have parted, either permitting a large bulbous mass to protrude from a widely gaping crack or, more commonly, disclosing a broad depression with a slightly convex floor

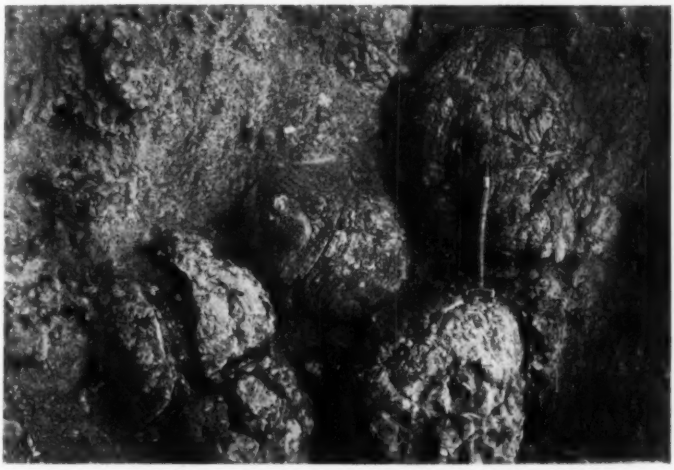

FIG. 1.—Basaltic ellipsoids embedded in granulated sideromelane at the northern end of a partially quenched basaltic flow, about 3 miles south of the mouth of Moses Coulee on the eastern wall of the Columbia River Valley. The effect of crustal displacement is apparent on the left. The hammer is 18 inches in length.

bounded on both sides by the steep margins of the crack. Although separated by a distance of even a foot or more, these miniature opposing escarpments would coincide fairly closely if placed in conjunction (Figs. 1 and 2).

Between these marginal walls and roughly parallel to them, a V-shaped depression is at least 2 cm. in depth. The upper margin of this medial depression curves outward on either side into a thick lip from which fragments have been irregularly plucked (Fig. 2). Closely parallel with these lips on either side are narrow ridges de-

[1] M. A. Peacock and R. E. Fuller, "Chlorophaeite, Sideromelane and Palagonite from the Columbia River Plateau," *Amer. Mineral.*, Vol. XIII (1928), pp. 369–80.

fined by superficial cracks spaced at an interval which ranges approximately from .5 to 1.5 cm.

FIG. 2.—A minor displacement in the surface of a basaltic ellipsoid showing at its center the V-shaped depression, which presumably marked the continuation of the initial crack. The ridges parallel to this crack are rather poorly defined. On either side contractional cracks of the original surface are apparent. This picture was taken about 100 yards to the south of the one shown in Figure 1.

Adjacent to the central depression, these ridges, as a rule, are also curved outward into a brecciated surface. Farther out, however, they assume a remarkable regularity which resembles a succession of miniature tilted fault blocks. The inner slope, instead of being rounded, rises from 2 to 5 mm. in height forming a slightly irregular scarp with an inclination of 40°–60°, while the flat outer slope, which is coarsely to minutely pitted, has usually a dip of 10°–30° (Fig. 3). The finest development of these ridges, which in the aggregate resemble a washboard (Fig. 4), occurs on large ellipsoidal masses where the sur-

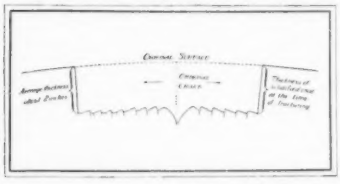

FIG. 3.—Diagrammatic sketch showing the displacement of a superficially solidified crust of an ellipsoidal mass.

face has been so greatly expanded that the original outer crust survives only as minor remnants.

Local alteration of the glass adjacent to these cracks renders their relation obvious in polished sections (Fig. 3). The major ones, which are seldom more than 4 mm. in depth, occur at the base of the steep slope. They are characteristically normal to the surface of the pillow rather than a continuation of the inclination of the scarps.

FIG. 4.—Angular corrugations on the surface of an ellipsoidal mass about 3 miles south of Vantage on the eastern wall of the Columbia River Valley.

Where the ridges are more symmetrical and both sides are inclined at about 45°, the pitted outer slope usually may be observed to be cut at its base by a minor crack which has permitted the formation of a flat depression between it and the adjacent scarp. In other cases, there is no visible displacement between the parallel units. In the latter instance, the surface as a rule is intensely pitted, but the glass immediately adjacent to the cracks is more resistant and stands out as thin walls.

On reaching the semiplastic glass,[1] the lower continuation of the

[1] C. N. Fenner, "Katmai Region, Alaska," *Jour. Geol.*, Vol. XXVIII (1920), p. 590; R. E. Fuller, "The Mode of Origin of the Color of Certain Vari-colored Obsidians," *Jour. Geol.*, Vol. XXXV (1927), p. 572.

deep crack, at which the crustal fragments separated, is considered to have been pulled apart to form a V-shaped medial depression. The extreme angularity of the adjacent ridges, the confinement of the pitted surface to their outer slope, and the close correspondence between the depth of the parallel cracks and the height of the miniature scarps indicate that they were formed by the rotation of superficially solidified crustal blocks. This rotation would have resulted in an enlargement of the surface and was, therefore, presumably induced by tension. Although the exact mechanics involved are problematic, the angular corrugations are considered to have been caused by the distension of a thin crust of homogeneous glassy lava as it was being rapidly exposed under water by the swelling of an ellipsoidal mass due to the settling of highly fluid lava.

FIG. 5.—Typical ellipsoidal mass showing locally concentric bands caused by the periodic advance of contractional cracks. This specimen is in the locality about 3 miles south of the mouth of Moses Coulee.

BANDED JOINT CRACKS

Many of the broken ellipsoidal masses exhibit locally concentric bands of different shades, parallel to their margins (Fig. 5). Series

of these bands are generally repeated several times at an interval of about 2 inches. On the outside, the glassy margin of the mass is, as a rule, partially altered to palagonite. At a depth of about half an inch, the surface of the joint shows a clean-cut grayish strip. Below this is a rough irregular brownish band appearing minutely granular. This in turn is followed by another strip of partially pala-

FIG. 6.—Bands caused by the periodic advance of a joint crack of a basaltic ellipsoid. The glassy outer surface is visible on the right. The dark bands are formed by a superficial coating of palagonitized sideromelane. Adjacent to them on the left is first the smooth surface and then the rough one caused by the crack encountering the still plastic lava. The area viewed is $4\frac{5}{8}$ inches in length.

gonitized sideromelane, which initiates a repetition of the sequence (Fig. 6).

These bands are due to the superficial variations in the lava adjacent to the major joint cracks. They appear to be confined to isolated ellipsoidal masses, where the cracks have been caused by tension induced by the contraction of the crust during solidification. These cracks presumably advanced periodically, cutting through the solidified lava with a straight fracture, but becoming irregular on disrupting that which was partially consolidated. The rough surface features of the inner layer are probably due both to the pull-

ing apart of the viscous lava and to the steam action caused by the water percolating down the crack. On encountering the still liquid lava at the base, the water would have chilled it to sideromelane and the steam would have partially altered it. With the solidification of the next layer of lava, the gradually accumulated strain would again have caused this crack to advance sharply, thus repeating the process.

FOSSIL IMPRESSIONS OF ICE CRYSTALS IN LAKE BONNEVILLE BEDS

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ABSTRACT

Strand sediments containing what appeared to be the fossil impressions of ice crystals were found by the writer in sediments of Upper Bonneville age in western Utah. A series of experiments were conducted to ascertain the conditions under which such impressions are formed. Criteria for the differentiation of such markings from other strand markings are briefly discussed.

INTRODUCTION

In 1927, while employed as field assistant by the U.S. Geological Survey, the writer discovered markings in strand sediments of Bonneville (late Pleistocene) age that appeared to be of ice-crystal origin. The fact that descriptions of such impressions are relatively few, coupled with the excellence of the specimens, has prompted the preparation of this paper.

J. A. Allen[1] has summed up the literature on markings of this kind and the following is quoted from his paper:

> In 1918 Dr. J. A. Udden[2] described certain markings he had observed in sandstone and limestone of Upper Cretaceous age in the Black Hills of Dakota and also the Big Bend district of Texas. He suggested that these markings represent fossil ice crystals. After presenting the field evidence and by comparison with recent ice-crystal markings he had observed on loess muds in Illinois, he concluded that ". . . . it appears to me that no doubt can be felt as to the origin of the markings in the fossil state."

Dr. John M. Clarke,[3] in 1917, described figured slabs of limestone of Upper Devonian age with short, rod-like markings which he called *Fucoides graphica*. These markings are not unlike some found by Dr. Udden.

Sidney Powers,[4] in 1921, suggested that the markings observed

[1] J. A. Allen, *Amer. Jour. Sci.*, Vol. XI (1926), pp. 494–500.

[2] J. A. Udden, "Fossil Ice Crystals," *Univ. Tex. Bull. No. 1821* (1918), pp. 1–8.

[3] J. M. Clarke, "Strand and Undertow Markings of Upper Devonian Time as Indications of Prevailing Climate," *N.Y. State Mus. Bull., No. 196* (1918), pp. 199–210.

[4] Sidney Powers, "Strand Markings in Pennsylvania Sandstone," *Jour. Geol.*, Vol. XXIX (1921), pp. 74.

by Dr. Clarke "represent casts of crystals or objects partly buried in the mud. . . . ."

Allen and his assistant, L. S. Russell, placed yellow river sand $\frac{1}{2}$–3 inches deep in shallow pans, and exposed them over night to temperatures from $-10°$ to $-30°$ F. A small excess of water was allowed to remain on the lower portions of the slightly inclined pans,

FIG. 1

thus producing a zone saturated by capillary action. These experimenters came to the conclusion that the fineness of the sediments and the degree of saturation were factors which have much to do with the type of ice crystals formed.

Ice-crystal markings were found by the writer in the Gold Hill Quadrangle, in western Utah, about 300 yards northwest of the town of Gold Hill. During Bonneville time the lake encroached upon the Deep Creek Range, and at this place drowned the lower course of a stream, thus producing narrow embayment several miles in length. A small delta accumulated at the head of the embayment during the period of maximum expansion of the lake. Later alluvium covered the deposits, but rejuvenation, due probably to the dis-

appearance of the lake, has brought to view the buff-colored, slightly indurated sands which comprise the delta. The total exposed thickness of the beds is from 2 to 4 feet, each stratum ranging from $\frac{1}{2}$ to $1\frac{1}{2}$ inches. The color and composition of the various strata are alike. Calcite, quartz, and tremolite grains, nearly all of which pass through a 150-mesh screen, make up most of the sediment.

FIG. 2

Markings, such as shown in Figures 1 and 2, are to be found in the upper surface of each stratum. The stratum of Figure 1 is $1\frac{1}{2}$ inches thick and the bed in Figure 2 is $\frac{1}{2}$ inch thick. The casts have a depth almost equal to the thickness of the layer.

During the winter of 1927 and the following early spring the writer observed the freezing of loess muds which cover the Columbia River Plateau in northwestern Idaho. Patterns strikingly similar to those shown by both Figures 1 and 2, with many gradations between, were seen nearly every morning for several weeks during the latter part of the winter. Flat areas of mud with nearly plane surfaces,

covered by a thin layer of water, usually gave the most uniform patterns. Homogeneity of the materials in size seemed also to favor uniformity of the crystal patterns. Such markings were never seen in coarse sands.

EXPERIMENTAL DATA

A large number of experiments were performed to duplicate, as nearly as possible, the ice-crystal patterns found in the sediments at Gold Hill.

The material used for the experiments was "bull quartz" which had been crushed in a small jaw crusher and then further reduced in a laboratory ball mill. Fine loess soils were also used in a number of experiments. The ground quartz was separated by means of standard Tyler screens into the following sizes:

	Through Mesh	On Mesh
1.	48-Mesh	65-Mesh
2.	65-Mesh	100-Mesh
3.	100-Mesh	150-Mesh
4.	150-Mesh	200-Mesh
5.	200-Mesh	

In some cases only one size of sand, as for instance through 48-mesh and on 65-mesh, was used; but, in other tests, material through 48-mesh containing all of the smaller sizes was mixed with definite quantities of water and frozen. A quantity of the sand sufficient to form a layer from $\frac{3}{4}$ to 2 inches deep was first spread over the bottom of the pan. Usually the sand was weighed so that the results of using different degrees of saturation could be compared directly. A measured quantity of water was then added by pouring it from a graduated cylinder down a glass rod, so that a small stream would trickle down the sloping side of the pan and be absorbed by the sand.

Close observation of the ice crystals formed by freezing the sand-water mixture showed them to be of bladed form, tapering to a knife edge, both downward and laterally. The great preponderance of the ice crystals thus formed stood vertically, with the narrow edge downward, but in some cases they were inclined at angles ranging from 45° to vertical. Invariably the ice crystals projected slightly above the surface of the sand.

The experimental data showed very clearly that, in order to produce ice crystals of such size that their casts may be preserved in

the fossil state, the sediments must contain gravitational water. By this it is meant that the interstices between the sand grains must be filled with water to such an extent that, if given the opportunity, water will drain from the sediment.

A coarse-grained sand mixture, such as through 48-mesh retained on 65-mesh, required a much greater saturation to produce noticeable ice crystals than a mixture passing through the 200-mesh screen. In both cases there was a migration of water from the interstices between the sand grains to the growing ice crystals. The coarse-grained sand-water mixture characteristically froze solid into a

FIG. 3

FIG. 4

monolithic mass of sand and ice with a uniform texture throughout; whereas, the minus 200-mesh mixture developed a network of ice crystals between the grains of sand.

It was very difficult to form definite crystal patterns with material as coarse as through 48-mesh retained on 65-mesh, although many degrees of saturation were tried.

Definite ice crystals were obtained in mixtures of finer and coarser sand, and the greater the proportion of the fine sizes to the coarse, the more readily the crystals formed. Sand passing through the 200-mesh screen formed ice crystals readily with a great variety of saturation and where the water-ratio was high the crystals were larger than in the cases where there was less water.

For the mixture used in Figure 3, 200 grams of minus 200-mesh

sand and 150 grams of water were used. The same kind and amount of sand used in Figure 3 was used for the mixture of Figure 4, but in this case enough water for complete saturation was added, and the surplus drained over the edge of the pan.

Very fine loess soil, all of which would pass through a 200-mesh screen, formed ice crystals at almost any degree of saturation. The most highly saturated mixtures always formed the largest and best-defined crystal patterns.

SUMMARY AND CONCLUSIONS

Experimental evidence indicates that ground-ice conditions, as was suggested by Powers,[1] are not necessary for the production of fossil ice crystals.

Ice crystals similar to those found at Gold Hill were observed to form naturally on flat surfaces of saturated loess muds in northwestern Idaho. The crystal impressions found in Idaho, coupled with those formed experimentally, leave little doubt as to the origin of the fossil ice-crystal impressions discovered at Gold Hill.

Ice crystals of sufficient size to develop casts that will survive the destructive processes of nature are formed from well-saturated sediments. The writer was unable to get ice crystals to form in sands coarser than 48-mesh. Mixing of fine and coarse sands tends to aid the formation of ice crystals. The most uniform patterns of large crystals were obtained from well-saturated sands that would pass through a 200-mesh screen. Experimental data indicate that the depth of the sand-water bed and the temperature at which the mixture is frozen seem to have little to do with the size, type, and pattern of the ice crystals formed.

Aside from being an index to the prevailing climate at the time of their formation, fossil ice crystals also serve as a criterion for the identification of the tops of beds. Many such markings have, no doubt, been passed over as drying or shrinkage cracks. While criteria for distinguishing fossil ice crystals from other strand markings have not yet been fully developed, it can be said that ice-crystal markings are much smaller in size and tend to develop along parallel lines rather than in polygonal patterns, as do shrinkage cracks.

[1] *Op. cit.*, p. 75.

MUTUAL RELATIONS OF POROSITY, VECTORAL PERMEABILITY, AND RESISTANCE TO EROSION

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ABSTRACT

Poorly indurated unstratified sediments such as loess and tuff are commonly resistant to erosion, whereas stratified sediments of similar texture may be very susceptible to erosion by running water. A case of silt originating from the redistribution of loess illustrates the principle. It is concluded that the orientation and concentration of platy minerals in certain laminae cause the rock to become impervious to water in directions transverse to the bedding, thereby increasing the relative amount of run-off. Since erosion is dependent on run-off rather than rainfall, erosion is greater on stratified deposits.

Gravel,[1] because of its porosity and permeability to water, has long been recognized as a resistant deposit. This resistance of gravel to erosion is expressed by its presence in ancient terraces, as cappings of hills, along prominent erosion scarps, and in other vulnerable places. In this article the writer calls attention to the fact that another deposit, loess, is similarly resistant to erosion, and analyzes the determining factors.

The summer of 1927 was spent in eastern Washington, making a study of the relations between the Palouse loess and its redeposited form, a silt. This silt has been described recently by Bretz.[2] The writer's study disclosed the significant fact that the water-laid material was much more susceptible to stream erosion than the loess from which it was derived.

OUTLINE OF FIELD SITUATION STUDIED

The Palouse loess covers much of the plateau country in eastern and central Washington, and the higher "island" hills in the scabland country. The scabland channels were cut into and through the

[1] J. L. Rich, "Gravel as a Resistant Rock," *Jour. Geol.*, Vol. XIX (1911), pp. 492–506.

[2] J Harlen Bretz, "Valley Deposits Immediately East of the Channeled Scabland of Washington," *ibid.*, Vol. XXXVII (1929), pp. 393–541; "Valley Deposits Immediately West of the Channeled Scabland," *ibid.*, Vol. XXXVIII (1930), pp. 385–422.

loessial cover,[1] showing clearly that the loess antedates the earlier Pleistocene, or Spokane glaciation. The waters which eroded the scabland channels backed up into several tributary valleys which

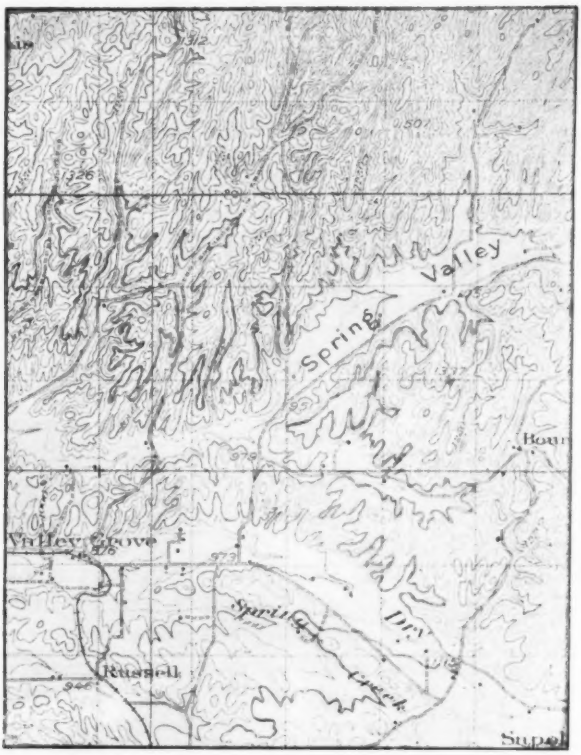

FIG. 1.—Portion of the Walla Walla Quadrangle (Washington). The 1,100-foot contour line is accentuated to show wind-controlled topography above and dendritic stream drainage below.

were not discharge channels, especially the Yakima and the Walla Walla, and in them deposited some of their load in the form of ex-

[1] J Harlen Bretz, "The Channeled Scabland of Eastern Washington," *Geog. Review*, Vol. XVIII (1928), pp. 446–47. (Includes bibliography of other papers on the channeled scablands.)

tensive silt deposits. The silts, therefore, also date from the time of the glacial waters.

The topographic character of the loess and the silt is strikingly different, both in the field and on the topographic map. The loess forms smooth rounded hills separated by broad mature valleys. The silt, on the other hand, develops a most intricate, dendritic drainage pattern. The silt, unlike the loess, is easily gullied, and forms steep slopes along streams. Eroded silt topography occurs below, and loess topography above the 1,100-foot contour line in the vicinity of Walla Walla. (See Fig. 1.) Below the 1,100-foot contour streams produce the intricate dendritic drainage pattern. Above the line the streams are clearly wind controlled, as shown by their parallelism and lack of tributaries. The purpose of this paper is to explain this difference in dissection.

CAUSE FOR DIFFERENCE IN DISSECTION

Since the deposits receive the same amount of rainfall, are composed of the same kind of material, and since age, if it has any effect whatever, should tend to make the loess the more dissected, the cause for the difference in dissection is to be found in some difference in the nature of the deposits. The chief difference in the nature of the two deposits is that the silt is stratified and the loess is not.

Redeposition of the material in water, and the consequent sorting and distribution of the variously shaped and variously sized particles in layers, seems adequate to account for the difference in resistance to erosion. The redeposited material is more impervious to water in directions transverse to the bedding, because flat particles have become concentrated and similarly oriented in certain layers. In the loess, on the other hand, although the flat particles are also present, they do not hinder the passage of water, just as in the silt certain layers are very pervious to water in directions parallel to the stratification.

Dissection depends on runoff. Since permeability in a vertical direction and runoff are inversely related, runoff will be greater on silt than on loess, and hence dissection will proceed at a greater rate with the consequent rapid dissection of silt and the comparative resistance of loess.

SUMMARY

Porosity and permeability are not necessarily related. Stratification in deposits containing flat particles decreases permeability vertically, but does not necessarily affect the porosity of the deposit as a whole, or the permeability in directions parallel to the bedding in certain layers. The imperviousness of a rock in a vertical direction determines the amount of runoff, which in turn determines the amount of dissection. Loess, because of its perviousness to water in all directions allowing a minimum runoff, is a relatively resistant deposit.

REVIEWS

Paleontology of the Jurassic and Cretaceous of West Central Argentina. By CHARLES E. WEAVER. "University of Washington Memoirs," Vol. I, 1931. Pp. 595; pls. 62. $15.00.

This monumental quarto publication is one of the most important monographs of invertebrate paleontology that have been issued in recent years. In the main it is a record of the purely scientific results of extensive field work carried on in 1922–25 for the Standard Oil Company of California. Although it is somewhat unfortunate that Weaver's detailed geologic maps cannot at this time be made public, nevertheless the company is to be congratulated for permitting the release of their paleontologic information. This is particularly true inasmuch as most of the organizations doing exploratory or developmental work in South America have needlessly withheld even those geological data which are essentially without economic significance.

Weaver, with four assistants, made a detailed examination of that part of Argentina which lies between the parallels 32° and 40° south latitude and the meridians 68° and 72° west of Greenwich. This area includes parts of the province of Mendoza and the territories of Neuquen, Rio Negro, and Las Pampas. Collections were made from over 2,000 stations, 300 of which were paleontologically fruitful. As a result 335 species of Jurassic and Cretaceous invertebrates are described, 69 of the forms being listed as new. Of this assemblage 170 species are from the Jurassic, 144 from the Lower Cretaceous, and 32 from the Upper Cretaceous, a few species being common to both systems. Pelecypods constitute essentially half the forms described, and the cephalopods, next in importance, make up nearly one-fourth the total. By adding the gastropods it becomes apparent that the molluscs are so dominant that only 18 per cent of the species listed belong to other phyla. There is, however, no statement as to whether this preponderance is real or only apparent. That Dr. Weaver believes in Gondwanaland is indicated by the fact that, in pointing out the similarity of the European and South American Liassic species, he says ". . . . since the majority of the forms are not free swimming types probably they migrated to this region along the north shores of the African-Brazilian . . . . continent."

The care with which the paleontologic studies were pursued is indicated

by the fact that much of the material was taken to the Geologische-Palaeontologische Institut of Bonn for comparison with European and other South American specimens. Weaver then returned to eighteen months of intensive laboratory study at the University of Washington. Still not content, in 1927 he returned again to Bonn, that European center of research on the geology of South America, with a collection representing all of his species; and six months more were devoted to a final biologic study of the material. Not the least important of the results of this European work was the securing of Herr Schilling of Hinterwald to execute the 52 beautiful plates of fossils.

Weaver, however, has been no mere collector and describer of fossils. He has done what more paleontologists should do, that is, he has determined lithologic compositions, areal distributions and variations, prepared detailed sections, and studied contact relations of all formations that have come under his observation. As a result he is able to give a detailed chart showing the lithologic and paleontologic interrelationships of a large number of typical sections; and he has been able to date these rather definitely with respect to the standard time scale. He also has been able to decipher the geologic history of the area. This may be summarized as shown in the accompanying table. (See page 183.)

In conclusion it is perhaps needless to say that it is easy to praise and difficult to criticize such a publication. Nevertheless, the reviewer cannot help protesting again against the well-nigh universal usage in geological circles of such phrases as "during the Lower Cretaceous" and "during the Upper Senonien" in place of "during the *early* Cretaceous" or "*late* Senonien." It is also to be regretted that the high price ($15.00) of the publication will, despite the fact that it is well worth the money, tend to prevent the widespread distribution which its general excellence bespeaks for it.

CAREY CRONEIS

A Descriptive Petrography of the Igneous Rocks. Vol. I. Introduction, Textures, Classification, and Glossary. By ALBERT JOHANNSEN. Chicago: University of Chicago Press, 1931. Pp. xxii+207; figs. 145. $4.50.

This very useful textbook deals essentially—indeed wholly—with petrography; petrology and its many problems are not touched on.

After brief discussions of the mineral constituents (chiefly devoted to such forms as trichites, spherulites, lithophysae, etc.), a chapter is devoted to the structures and textures of igneous rocks, the distinction between the two made by C. I. P. W. being recognized, although such structures

QUATERNARY				Uplift of present Andes in fault blocks as result of tension
TERTIARY				Outpouring of andesitic lavas and tuffs Uplift of early Tertiary Andean range as the result of compression
UPPER CRETACEOUS	Danien-Maestrichtien Senonien		Roca formation	Atlantic marine transgression
MIDDLE CRETACEOUS	Turonien		Pehuenche formation (upper red beds)	Dinosaur fauna
	Cenomanien Gault-Albien		Lower red beds	Continental deposition Mountain making in Southern Neuquen
LOWER CRETACEOUS	Aptien Barremien Hauterivien		Agrio formation	Mountain making in Southern Neuquen West Central Argentina widely flooded
	Valanginien	Upper Middle	Mulichino formation	Continental deposition in Central Neuquen
		Lower	Quintuco formation	Marine deposition
UPPER JURASSIC (Malm)	Tithonien		Widespread marine deposition in West Central Argentina	
	Lusitanien, Loteno formation		Uplift of Central Argentina. Continental sandstone	
	Oxfordien		Widespread deposits of gypsum	
	Callovien		Intercalations of marine calcareous sandstones in massive continental sandstones	
MIDDLE JURASSIC (Dogger)	Bathonien		Widespread uplift and drainage. Continental sandstones	
	Bajocien		Widely flooded embayment during early Bajocien, shallow seas and withdrawal during middle, and erosion during late	
LOWER JURASSIC (Lias)	Lias		Shallow seas and contemporaneous volcanic action	
TRIASSIC	Triassic		Shifting fresh water basins. Temporarily the sea gained access to Southern Neuquen. Marine deposits in Central Chile. Crustal down-warping and origin of the West Central Argentine marine basin of deposition	
	Pre-Triassic		Carboniferous and Permian deposits including glacial materials and granites	

as columnar and pillow basalts and platy parting are regarded as belonging to petrology, rather than to petrography (p. 34). Little is said of structures, but the microscopic textures are very well described and are illustrated by many photomicrographs, most of which are excellent (except that of "trachytic texture," Fig. 72, which is not typical).

In ten succeeding chapters (103 pages) all the prominent systems of classification of igneous rocks are discussed, and the more modern quantitative ones are very well summarized, their appropriate formulas being given. The author states that his own system will be used in Volume II, "which will define the various rock families, giving both megascopic and microscopic characteristics." This array of classifications, some twenty or so in all, which must be very bewildering to the beginner, confirms the reviewer in his opinion, long ago arrived at, that most, if not all, attempts at the *exact* classification of rocks are more or less futile and unsatisfactory. He thinks that rock classification may easily be carried to too great detail, and that many of the modern refinements are uncalled for, both in classification and in nomenclature. It seems to the reviewer that some of the older and rougher classifications will serve most purposes, with a certain amount of recognition of quantitative relations, and with some modifications and additions to meet the needs of advancing knowledge. After all, the correct fundamental basis of the classification of igneous rocks has not yet been found, and past and present systems, whether chemical or modal, are essentially classifications of the resultants of forces and processes that are as yet little known, but which, in the reviewer's opinion, should be regarded as a fundamental feature of the classification.

As was pointed out by Iddings many years ago, igneous rocks intergrade in all directions and in all possible ways, so that any exact divisions must be arbitrary. This is recognized in most of the modern quantitative classifications, such as those of C. I. P. W. and of Johannsen. In this connection it may be of some historic interest to record that attempts were made about 1901 by C. I. P. W. to utilize various representations of double triangles and tetrahedra, with quartz opposed to the feldspathoids and with the feldspars and the femic (or mafic) minerals at the sides, much as is suggested by Johannsen. These were all abandoned by us, chiefly because of the arbitrary and artificial character of the subdivisions involved and because they seemed to be too complex for practical use. The reviewer still has one of these unused attempts and possibly may publish it one of these days. While this is not the occasion to discuss the broad subject of rock classification, it may be said that, in the opinion of

the reviewer, the chief merits of the C. I. P. W. classification are the suggestion of quantitative relations, at that date scarcely recognized (and possibly carried by us into too great detail), the idea of the norm, and the use of such terms as "salic," "femic," and "mafic."

Johannsen uses throughout many of the terms proposed by him some years ago, such as "sodaclase," "pyribole," "quarfeloid," and "foid." To some of us it seems that it is rather hard on the student beginner, and in a way not giving quite a "square deal," to call on him to use such technical terms, which, whatever be their merits, have not yet been adopted into general petrographic literature, in place of many in common use.

Rock-forming minerals are not described, but their microscopical determination is dealt with in another work by the author (1928). The great majority of the definitions in Appendices I and II are good, and the list is almost complete. These and the summaries of the various classifications are among the most valuable parts of the book. The well-known tables for the molecular numbers of the chemical constituents of rocks and for calculating the percentage weights of the normative minerals are reprinted from *Professional Paper 99* of the U.S. Geological Survey. In Table XLV (taken from von Eckermann's *Molecular Quotienten*), they are based on the atomic weights of 1911, where they are carried out to six and seven places of decimals. Such ultrarefinements are uncalled for, in view of the variation in composition of different parts of many rock specimens, and in the tables given by C. I. P. W. only the rounded atomic weights are used. This would seem to be justified for the reason given above and because of the recent discovery of isotopes. The many portraits of petrographers are an interesting addition, but the author very modestly does not include one of himself. The "get-up" of the book is very good and there are remarkably few misprints, the only serious one noted being on page 55, line 6, where 1919 should read 1902.

Notwithstanding the use of the author's technical terms, the book may be recommended as a useful, elementary, modern presentation of petrography. The appearance of Volume II will be awaited with much interest.

HENRY S. WASHINGTON

Journal of Sedimentary Petrology. Vol. I, No. 1, (May, 1931).

A journal published semi-annually by the Society of Economic Paleontologists and Mineralogists, a division of the American Association of Petroleum Geologists.

This journal, the newest of publications devoted to some phase of geology, is an expression of two things. First, it indicates to what extent

specialization has gone in the field of the geological sciences; and, second, it expresses the growing interest in the sediments and sedimentary rocks. This latter expression has been evidenced through the past decade by the establishment of courses in "sedimentation" and of a "Committee on Sedimentation," and by an increasing number of "sedimentationists." And now we have a culmination of this interest in a journal devoted exclusively to the field!

Most significant, perhaps, is the name of the new journal. Until recently, in this country at least, the "sedimentationists" have been largely men trained in stratigraphy and paleontology. And hence their approach to the study of sediments is necessarily limited. But "sedimentation" is, after all, merely a general term covering processes and is consequently only a part of the larger field of sedimentary petrology, the science dealing with the nature and origin of sediments, whose problems can only be solved by the combined efforts of petrographer, mineralogist, stratigrapher, paleontologist, and technologist.

In the Foreword by the editor appears this statement: "Since the Society is concerned with problems of oilfield discovery and development, it is desirable that contributions accepted for publication in the *Journal of Sedimentary Petrology* should have bearing, directly or indirectly, on this *raison d'être* of the Society."

It would truly be unfortunate if the desirability became a necessity. However, the present number appears not to be so unfortunate since a résumé of the contents shows papers varying from the measurement of the shapes of rock particles and the petrography of bottom samples from the North Pacific Ocean to the clay minerals and their identification.

Significant also is the recognition of the quantitative aspects of sedimentary petrology in a considerable number of the published papers. It has become very evident in recent years that little progress can be made in this science without more exact data. And such exact data must be quantitative. The quantitative determinations of mineral composition, a reduction of the shapes of detrital grains to mathematical formulae, particle-size studies by new methods and apparatus illustrate this aspect of the science.

So recently has this quantitative aspect of the field developed that the science has been until now in a state of stagnation, despite the fact that the number of papers on "sedimentation" is legion. Much has been written, but little has been done to develop new methods and apparatus without which there can be no advance. A rapidly changing viewpoint, from stratigraphic and paleontologic to petrographic, coupled with the stimu-

lus of potential economic application of principles evolved, brings the study of the sediments really to its beginning as a science. A journal devoted to this field which will "foster research in the subject in every possible direction" has, therefore, a justifiable existence, and is welcomed by students of sediments.

F. J. P.

Geologic Cross-Section of the Central United States. Prepared under the chairmanship of ANTHONY FOLGER. Wichita, Kansas: Kansas Geological Society, 1931. $8.00.

This compilative work, covering a line 1,960 miles long from Lake Superior to the Rio Grande, is a blueprint 280×130 cm. The lithology is shown by conventional symbols, and a legend is given, so that the various geologic systems may be made to stand out if the section is colored. The vertical scale is exaggerated 264 times. At first glance this seems too large, and one might think that 100 times would have been more appropriate. But this question was carefully considered by the committee, and such exaggeration seemed advisable in order to show units as thin as forty feet. Any section not to the same horizontal and vertical scales is a compromise. The chief advantage of exaggeration is to show stratigraphic detail; the drawbacks are the distortions of dip and the thickness of dipping beds. Thus on the north flank of the Arbuckle Mountains the Arbuckle group apparently thickens greatly as it dips away from the mountains; actually a considerable thinning takes place. The evils of dip exaggeration may be counterbalanced in part by drawing a dip diagram on the chart using the following data:

True Dip (Degrees)	Apparent Dip (Degrees)	True Dip (Degrees)	Apparent Dip (Degrees)
0	0	5	66½
1	25	10	78
2	43½	25	85
3	55	45	88½
4	62	90	90

Included on the blueprint are a Cambro-Ordovician correlation chart and a tectonic map of the region. The accompanying guidebook contains descriptions of the various parts of the section together with correlation charts for the Mid-Continent area (including Texas).

In the main the cross-section is based on subsurface data. The wealth of detail shown, which may be considered as the cream skimmed from the maze of facts discovered from the extensive drilling of the past decade or

two, makes it desirable that this chart be in every geological library, both in the United States and abroad. The Kansas Geological Society has rendered the general geologic profession a real service, and it is hoped that sales will be sufficient to keep the financial loss within reasonable bounds.

D. J. FISHER

Petroleum in the United States and Its Possessions. By RALPH ARNOLD and WILLIAM J. KEMNITZER. New York: Harper & Bros., 1931. Pp. 1052. $12.50.

This excellent treatise on petroleum in the United States and its possessions is invaluable to those interested in any phase of the petroleum industry. It is a very complete encyclopedia concerning the occurrence and production of petroleum in this country. The authors have drawn freely on the literature of the federal and state surveys, as well as many of the scientific trade journals. The book is largely a compilation of facts, and as such fills a long-felt need as a handy reference book.

The book is divided into two parts. Part One analyses the production areas. It includes an excellent summary of developments in the United States, followed by a detailed discussion of the major fields, which in turn are divided into smaller geographical units. The history, geology, technology, and economics of petroleum production with an estimate of future possibilities of each productive area are separately analyzed and evaluated. A bibliography of selected references dealing with geology, technology of exploration, development, and production accompanies each geographical unit.

Part Two discusses the possibilities of finding petroleum in the non-productive areas. These are treated in the same manner as productive areas, but in much less detail. States and possessions are arranged alphabetically.

Two very excellent colored maps are included which alone are well worth the price of the book. One is an outline map of the United States showing the present proved oil and gas fields, and a classification of land for petroleum; the other is a geologic map of the United States revised to 1930. Unfortunately no maps of the major oil fields or state maps are included.

The book has three very complete indexes: authors in bibliographies, subjects in bibliographies, and an index to the text.

DOLLIE RADLER

Lehrbuch der Geologie. III. Teil. Geologische Länderkunde. By F. X. SCHAFFER. Leipzig and Wien: Franz Deuticke, 1930. Pp. 96; figs. 68.

Instead of basing his textbook largely on certain selected portions of the earth's surface, the author has recognized that in distant regions the geologic manifestations are different, and hence the advantage of a comprehensive treatment covering the earth as a whole. Europe, North America, Northern Africa, and portions of Asia having formed the basis of the two previous volumes, Part III is devoted to Polynesia, Australasia, Antarctica, and India. In 1925 and 1927 the author made two extensive journeys to acquire personal familiarity with these southern regions, and his own observations have aided materially in co-ordinating the general geology of these portions of the globe.

Chapters are devoted to: I, Pacific Region, comprising (*a*) the relatively undeformed Pacific basin and (*b*) the Austral-Polynesian orogen (New Guinea to New Zealand); II, Australian Continent; III, Antarctic Continent; and IV, Peninsular India. Genetic and tectonic relationships are kept ever to the fore and are made to bind together the different regions. The purpose of the treatment seems to be to afford an adequate bird's-eye view by including just enough of the local details to delineate the larger relations in proper perspective. In this the author has been very successful and his pages are recommended to the geologist interested in the comparative geology of the globe.

R. T. C.

General Stratigraphy. By J. W. GREGORY and B. H. BARRETT. London: Methuen and Company, Ltd., 1931. Pp. 285; figs. 46. 10*s*.

The authors have presented in this volume a brief outline of the general stratigraphy of the globe. Naturally Europe receives the most detailed treatment, but the unusually extensive travels and studies of the senior author in other continents have made possible an appreciative treatment of the main features of the geologic succession for the earth as a whole. An average of about fourteen pages to each geologic system does not admit of great detail or much deployment of alternative interpretations where there has been difference of opinion. But a geologist, nevertheless, will find this volume packed with useful information in concise form, and will profit from the boiling-down process to which the material has been subjected. Most useful to him will probably be the comprehensive view

of the stratigraphy of continents, other than his own, thus made readily available.

Many geologists, however, will probably object strongly to the map of the world in the Cambrian period (p. 53), which makes the entire Southern Hemisphere land, with the exception of one small area of sea in Brazil, two others in the East Indian Archipelago and Australia, and another little sea south of Tasmania. Is it not time to vote a holiday in extending our paleogeographic maps to include the present ocean basins until we really know something about them?

R. T. C.

New Oil and Gas Map of New Mexico. By DEAN E. WINCHESTER. Socorro: State Bureau of Mines and Mineral Resources, 1931. Paper, $1.00; cloth-backed, $1.50.

This map on a scale of 1:1,000,000 is printed in two colors, the base being in black, and oil and gas data in red. The axes of nearly 200 anticlinal structures are shown and also the location, total depth, and results (by symbol) of approximately 1,000 wildcat wells. Known oil and gas fields are indicated by patterns and the location of all main oil and gas pipe lines, refineries, and gasoline plants is shown.

R. T. C.

Natural Gas Sands of Eastern Kentucky. Series VI, 1930. By W. R. JILLSON, Director and State Geologist, Kentucky Geological Survey. Frankfort, Kentucky.

Natural Gas Sands of Western Kentucky. Series VI, 1931. By W. R. JILLSON, Director and State Geologist, Kentucky Geological Survey. Frankfort, Kentucky.

These are correlation charts, in colors, of the gas fields of Kentucky. They are based on well records and include thirty-five gas pools. Two datum planes are used, one on top of the Chattanooga–Ohio black shale, which is correlated as Devonian, and the other at the base of the "Big Lime" which is Mississippian. Notable features brought out by these charts are the thickening of the Mississippian limestone toward northwestern Kentucky and the thickening of the Chattanooga black shale toward the northeast. No attempt has been made to indicate structural features.

PAUL H. DUNN

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